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The domain in which chemical synthesis exercises its creative power is vaster than that of nature herself.

MARCELIN BERTHELOT
(1827-1907)

The future belongs to Science. More and more she will control the destinies of nations. Already she has them in her crucibles and on her balances.

SIR WILLIAM OSLER
(1849-1919)

INTRODUCTION

by Glenn T. Seaborg

THERE are two main social purposes in writing a popular science book of the type of *Chemistry Creates a New World*. One is to encourage young people seriously to consider entering science as a career. The second is to make clear to all of us how the developments of science have a basic importance which cannot be ignored and which, if understood, can help us to make more intelligent decisions in our personal and community lives.

Bernard Jaffe has sought to achieve these purposes by describing for us a dazzling multiplicity of chemical marvels which have revolutionized modern society in the fields of metallurgy, agriculture, medicine and public health, industry, transportation, warfare, and in countless other fields. He has done this skillfully and accurately and, by liberal use of anecdotes and case histories, has made this a highly absorbing story. Particularly well done are his accounts of the crucial struggles during World War II, in both the allied and the axis camps, to develop sufficient tonnages of essential products, which were not available from the usual sources. These passages make quite clear that the statesman, the politician, and the military planner must all be aware of the world of chemistry and of science and engineering in general.

This is not a book of chemical principles and does not attempt to explain how a scientist goes about making his discoveries. To communicate a significant awareness of these matters would require going into the subject more formally than is perhaps possible in a popular account. In a way, this is too bad, since the result in the eyes of the layman is to make of the scientist a towering genius who conjures up these miracles from his test tubes and electronic circuits in a completely mysterious way. We can

read about a great musician or a great athlete and, although we know that we ourselves could never hope to achieve his masterful control of mind and muscle, we do not regard these people as mysterious. We know that if we underwent a regime of training we could ultimately learn to play a musical instrument with some competence or manage to clout a golf ball around an eighteen-hole course without building a score that is outrageous.

Actually the workings of science are no more mysterious. Not all of us have the natural aptitude to learn the fundamentals, but a very sizable proportion of our young people do have the natural ability to gain scientific skills sufficiently well for interesting, rewarding, and productive careers. Science is an organized account of the facts and principles developed by our predecessors and an organized method of proceeding from these to discovery of new uses for them, or to discovery of new facts and principles. The systematization and the methods are quite straightforward and can be learned by any intelligent person willing to put in the effort required. Once learned, they will lead with certainty to useful or original scientific or engineering achievement. Without them the most outstanding genius is as helpless as the most stupid to conjure up a scientific miracle.

As we look into the future we can be absolutely certain that science will play an ever increasing role in the aspects of our lives discussed in this book. Our population increases at a rate something over one and one-half per cent per year, and will certainly be double its present value in the year 2000, a time which most school children now alive will live to see. This means an increase in our technology, using this term in a very broad sense, of something very much more than double its present level; because, in order to support a larger population with the same natural resources, science is called upon to increase efficiency of old methods and to develop substitute methods and materials.

The well-being of our country requires that a much larger proportion of our youth choose careers in science. A young person electing to study science, either preparing for a career or to learn enough to aid him in another field,

will be certain to find stable employment for his services and work which is rewarding financially and in satisfaction.

The person who wishes to be regarded as cultured cannot afford to neglect some study of science. I define a cultured man as one who is aware of the nature of his physical environment and of his own nature, who understands the origins of his social, religious, governmental, and political institutions and of the ideas on which they are based, and who, because of this knowledge, has some basis, if he so desires, on which to make intelligent decisions in adjusting to his present environment or in changing it to a better one if he finds it unsatisfactory. The cultured man of today can no more ignore science than the cultured man of the Middle Ages could ignore the Christian church or the feudal system.

The author of this introduction is a scientist who has spent his life in research in the field of chemistry and physics. Perhaps he can be pardoned for speaking out so stridently for the importance of his own specialty. Though there is natural prejudice, the thesis is nonetheless true, and is widely recognized as true by nonscientists who have worried about present trends in our society. It is not meant to deprecate the importance of all other lines of activity in this interdependent world of ours. Trained brain power of all varieties is absolutely vital to our future and will become more so as the destinies of the countries of the world become ever more intertwined. The scientist can only protest that the extent to which science and technology have entered every corner of our social, economic, and political lives is very dimly perceived by most people, and that a wider understanding of it would have beneficial consequences.

I recommend *Chemistry Creates a New World* to you because it is interesting. If, in addition, it achieves in some way the other noble purposes which I have discussed—well, so much the better.

University of California
Berkeley, California

PREFACE

DURING the past twenty years only about half of our high schools offered courses in chemistry each year, and only about seven per cent of the total high school registration elected to study the subject. As a result, millions of otherwise intelligent adults are now either completely ignorant of what chemistry means or, at best, have a rather fuzzy understanding of it. Even students who were exposed to a year or more of elementary chemistry in college have generally failed to keep abreast of the rapidly advancing front of the new alchemy.

Practically unknown to these millions of people, several minor chemical revolutions and one convulsive upheaval—liberation of atomic energy, affecting the lives of every inhabitant of this planet—have occurred during these two decades. For the first time in history the chemist has solved the problem of cheap, high-quality, man-made rubber. The rubber in the tires of your car is mainly synthetic. We can, if we so desire, be completely free of the rubber tree in faraway Indonesia, Malaya, and Ceylon. Similarly, the chemist with test tube and flask has made it possible to manufacture gasoline and lubricating oil from any grade of coal, at a cost competitive with that of gasoline refined from crude petroleum. We no longer have to depend on the petroleum resources of the troublesome Middle East, or even on our own continental and offshore crude reserves.

The chemist, too, has taken on the job of synthesizing vital hormones, vitamins and drugs that were hitherto obtained from natural sources often located in foreign countries. He has synthesized quinine, strychnine, cortisone, and streptomycin. He has put together a powerful array of new chemicals which in the hands of physicians have all but wiped out some of mankind's worst killers and cripplers. Three fourths of all the medicines sold over the drug store counter today were nonexistent twenty years

ago. Overshadowing all of these triumphs is the development and control of atomic energy for industrial use. From the nucleus of the atom man now commands an unlimited and widespread reservoir of energy which can raise the living standards of hundreds of millions all over the globe.

These are only a few of the vital and dramatic advances in chemistry that everyone should know about. Not only is chemistry a part of the physical world we live in, but it is also part of our cultural environment. A person who prides himself on his knowledge of music, art, or literature while deliberately ignoring science is not well-rounded intellectually. Such an attitude may be partly due to the fact that scientific information is more specific and difficult than the arts, and partly to his never having been properly introduced to the human and esthetic values of science. In time, people who avoid science may even become suspicious or fearful of its supposed mysteries.

Today, when progress in chemistry is so breathtakingly rapid, when new and challenging projects are being undertaken and financed by billions of dollars of private and public funds, when critical issues involving a knowledge of chemical facts must be intelligently resolved and when our productivity has multiplied many times, giving us more leisure to explore other fields, the work of the chemist should be better understood by everyone.

In conversation with alert and thoughtful people of all ages I discovered a widespread desire for a simple basic understanding of chemistry and its major achievements, especially those of the last two decades. The need is for facts, not sensationalism; for established principles, not Sunday-supplement theories; for an elementary exposition that is neither too detailed nor too simplified; and for a story that demonstrates the impact of this chemical revolution on the lives of ordinary people in all walks of life.

In an attempt to meet this need I have set down in plain language some of the basic information of rudimentary chemistry in the first three chapters, followed by an account of the thrilling story of present-day creative chemistry. Einstein once said, "For us science is an end in itself because we scientists are an inquisitive lot. But we cannot expect every layman to feel about it the same as we do,

and he has the better claim, therefore, to special consideration."

The present work was written to give the nonscientist some of this special consideration. It may, it is hoped, even inspire him to further reading and study on a fascinating subject.

I would like to express my sincere thanks to James R. Newman who started me thinking about this book.

BERNARD JAFFE

1 What Is Chemistry About?

Did you ever stop to consider what kind of world this would be if all the facts and know-how of modern chemistry had never been discovered or developed? And when I say modern chemistry I mean the chemistry that had its birth about the time that the Declaration of Independence was signed in Philadelphia. For it was less than two hundred years ago, on August 1, 1774, that an English minister—who was forced some time later to seek refuge in our newborn Republic because of his political and religious beliefs—discovered the chemical element oxygen. This event, which soon led to the first correct explanation of the common chemical change known as burning, marked one of the great turning points in human history.

Of course, even deprived of the benefits of modern chemistry, you could still gaze in wonderment at the massive structures of the Pyramids and the stained glass windows of Chartres. You could marvel at the fabulous steel blades of Damascus and the exquisite glass of the Venetians, stand in awe at the paintings of Da Vinci and the sculpture of Michelangelo, and thrill to the works of Bach and Shakespeare. You could even point to the worldshaking contributions of such men of science as Galileo and Newton.

Yet it would still be a world in which a newborn infant's life expectancy would be only 35 years—half that of an American child today. It would be a world in which man would still be earthbound, with no wings to fly, no jet planes to thrust him from New York to Paris in less than four hours at supersonic speed, and no space capsule to orbit him around the earth in less than 90 minutes. It would be a world in which transmission of voices and images through the air would be looked upon as the dreams of simple-minded or overcredulous people. It would be a sorry place for those who had to endure the pains of surgery or the fevers of illness, for the great pain-

killers of modern times would be unavailable. In short, would be a world which physically, at least, would not b much different from the world of Franklin, or Jefferso or Washington.

How has chemistry transformed this planet of ours s profoundly and in such a relatively brief time? To unde stand this tremendous change—and even more important fully to understand your morning newspaper, and th chemical achievements of the past twenty years that hav figuratively turned the whole world on its ears—you shoul have some basic knowledge of chemistry and its applica tions.

I will not stop to give you an all-inclusive or highly technical definition of the science of chemistry at this time It would have too little meaning for you. For the present it will be enough to say that chemistry deals with the make-up or compostion of things—the rocks of the earth, the water and salt of the sea, the air we breathe, the paper we write on, the food we eat, the rubber we roll on, and the medicines we take—to mention just a few.

Chemistry also deals with the myriad ways in which substances change or behave in the presence of other substances. For instance, the chemist is interested in knowing why a steel girder rusts when exposed to the atmosphere, why a photographic film impregnated with certain chemicals darkens after being exposed to light, what takes place when food is transformed into tissue in the process of digestion, in what mysterious manner some antibiotic seeks out a bacterial invader and destroys it, why the green foliage of the forest gradually bursts into a blaze of color with the approach of autumn, and why the bombardment of a piece of uranium with tiny particles of matter called neutrons may set off a cataclysmic explosion. Finally, chemistry also includes the study of the energy changes that accompany chemical changes, such as the evolution of heat, light, or electricity.

Chemistry, in other words, is concerned with any gas, liquid, or solid you can name, animate or inanimate, forming a part of this globe or of any moon or planet or sun among the trillions of stars that spangle the heavens. That is a lot of territory—the whole universe, in fact; but the

universe is, indeed, the province of the modern chemist. More than that, the chemist has created brand new things that nature never got around to making—man-made artificial dyes that rival the colors of the rainbow; synthetic fibers that surpass the products from sheep, silkworms and cotton fields; drugs more potent than any mineral, herb, or animal extract yet distilled.

In a certain sense, however, this seemingly boundless world of the chemist is not so endless a realm as you might imagine. It is really bound by the limited outlines of a handful of elementary particles.

Twenty-four centuries ago, when Greece and Asia Minor were the world centers of power and culture, some of their philosophers, particularly Empedocles, turned from applied arts such as the working of metals and the dyeing of textiles to an interest in theoretical speculations. They attempted to prove an underlying unity in this vast collection of different things by suggesting that there were actually only four basic or elemental substances, from which all other material substances were derived. All things, they said, were composed of one or more of these four simple elements—fire, air, earth, and water. They reasoned somewhat like this: Air, of course, was necessary to life—no argument here. Water, too, was essential to the growth of plants and to the health of all living things—again no valid objection. Earth—well, that was the solid stuff of which their world was built—only a stubborn mule of a philosopher would argue about this. Fire—that was a power before which all men stood in fear and which many men worshipped; it could certainly not be excluded from any list of the basic elements.

This concept of four primary elements, independently arrived at even earlier in India and China, and by the ancient Egyptians, was later modified by Aristotle, the great philosopher and teacher of Athens. It became deeply rooted in the ancient world and for centuries resisted every attempt to dislodge it. While the sages who preached this doctrine did not bother to produce any rigorous proof or objective evidence in support of it, they would, if pressed hard enough, offer the visual proof of a burning green twig. As the wood burned, they called attention to the all-

consuming fire, the water that boiled off the ends of th twig, the smoke or air that rose from the expiring wood and finally to the ash or earth that was left after the twi had disappeared.

Pretty flimsy evidence, you might say, but who in all o Greece and Ionia had richer proof or a more plausibl explanation? They would not trouble to experiment; tha was manual labor fit only for slaves. To counter some o the objections occasionally raised against this idea of fou elements, some of the ancient philosophers and their fol lowers endowed each of the four elements with a pair o opposites—warm or cold, wet or dry. Fire was hot and dry, earth was cold and dry, water was cold and moist and air was hot and moist. With this they proceeded to build up a fantastic system of combinations of elements and opposites to account for all the properties of different things. This enrichment had the dubious virtue of putting a halt to further questionings by the introduction of greater confusion. The still later addition of three so-called "principles" of matter—namely salt, sulfur and mercury—was no improvement.

But as the years rolled on and more knowledge accumulated, some men wondered how copper and iron, tin and lead, sulfur, carbon and mercury, and silver and gold—elements known since the dawn of history—could be logically fitted into this very exclusive "four-element" or even "seven-element" notion. Doubts about the soundness of the principle began to multiply as more and more basic substances were uncovered. Old beliefs die hard, and it was not until after the middle of the seventeenth century that an Irishman finally slew the "four-element" hypothesis. Robert Boyle, known to some of his fellow countrymen as the "Father of modern chemistry and Uncle of the Earl of Cork," published a book in 1661 entitled *The Sceptical Chymist*. In it he set down for all to read the first scientific definition of a chemical element.

"To prevent mistakes," he wrote, "I must advertise to You, what I now mean by Elements: certain Primitive and Simple, or perfectly unmingled Bodies, which not being made of any other Bodies or of one another, are the Ingredients of which all those call'd perfectly mixt Bodies

are immediately compounded; and into which they are ultimately resolved: now whether there be any one such Body to be constantly met with in all, and each, of those that are said to be Elemented bodies, is the thing I now question." This celebrated definition translated into modern English simply said that a chemical element is a single, pure substance that cannot be broken down into anything simpler even by the most violent physical impact or the most deep-seated chemical change.

Boyle made another important contribution in this field. He introduced the term *analysis* to designate those chemical properties and changes which could be used to distinguish individual substances one from another.

As of this moment we know that everything on earth and in the myriad suns blazing in the darkness of space millions of light years away, yet reached by the invisible fingers of our gigantic telescopes—all of this universe is composed of one or more of the 103 chemical elements existing in nature or newly created by man. The man-made elements, eleven of them, will be discussed in detail in the next to last chapter of the book. Some of the remaining ninety-two of these elements occur normally as gases, such as colorless oxygen, nitrogen, and hydrogen, as well as poisonous chlorine, and deadly fluorine. Most are solids, such as iron, and six other metals known to antiquity —as well as nickel, chromium, tungsten or wolfram, platinum, boron, aluminum, sulfur, bismuth, carbon, phosphorus, and uranium. Only two of the lot, bromine and mercury, are liquids under normal conditions. You probably have heard of most if not all of these elements. Here are some of the others with names less familiar and therefore more forbidding—praseodymium, neodymium, samarium, gadolinium, terbium, dysprosium, and thulium.

The elements were tossed into the earth's hopper with evidently no regard to equality. For example, half of the composition of the earth's crust, ocean, and atmosphere is oxygen. Next come the element silicon (26%), and the metals aluminum (7.5%) and iron (4.7%). In fact, only nine elements together account for more than 99% of the solid crust of the earth to a depth of ten miles. Some, such as krypton gas, occur in the atmosphere to the extent of

only about one part in 20 millions, and its sister element, xenon, one in about 170 million parts of air.

From this mere handful of chemical elements joined together by invisible bonds in an almost limitless number of combinations come the hundreds of thousands of chemical compounds discovered in nature or manufactured for the first time in the chemical laboratory. Some of these compounds are familiar to you, such as pure sand, table salt, sugar, and baking soda. Sand is composed of two elements, silicon and oxygen; table salt also of two elements, sodium and chlorine, sugar of three—carbon, hydrogen and oxygen; baking soda contains four elements—sodium, hydrogen, carbon, and oxygen.

A chemical compound, as you have probably already gathered, is a substance composed of two or more elements chemically combined. During this chemical change, the elements lose their individual properties and entirely new substances are formed. Compounds have characteristics of their own. They can be recognized by these properties, which are always very different from the properties of the individual elements that compose them. For instance, the compound sodium chloride, or table salt, is a white solid that has a salty taste, dissolves in water, and is very stable —that is, it does not change easily into other substances. It is essential to most diets. The two elements which compose it are dramatically different individuals. Sodium is a soft, silvery, fairly light metal which is so violently active that it must be kept scrupulously away from any air or water. With the oxygen of the air it combines with unusual zest, burning to a white powder. With water it reacts spontaneously and with great avidity, destroying the water and liberating huge volumes of a combustible gas called hydrogen. Its chemical partner, chlorine, is a very vigorous personality too—a yellow greenish gas, extremely poisonous when inhaled, and very eager to combine with most other elements. The simple act of chemical union of these two elements tames both of them and transforms them completely into the sober, highly essential compound, sodium chloride.

Besides elements and compounds there is a third and final class of substances which are known as mixtures.

These may contain one or more elements or compounds, or both, not chemically united but mechanically or physically mixed together. The ingredients of mixtures, unlike the elements present in compounds, may be physically separated without the use of chemical methods. For example, crude oil or petroleum is a natural mixture of many different gases, liquids, and solids which are fairly easily separated by a physical method such as heating, since the different individual components boil off at different temperatures. Milk is another mixture, made up approximately of water (87%), butterfat (4%), casein (3.3%), milk sugar (5%), and smaller amounts of vitamins and mineral compounds. All of these may be separated from each other by mechanical or physical means, such as allowing the butterfat to rise to the top and then skimming it off from the rest of the ingredients. Then, of course, there is the air around us. Air is a mechanical mixure of about 21% oxygen, 78% nitrogen, less than 1% argon, and minute amounts of the other inert gaseous elements—helium, neon, krypton, xenon, and radon—plus about 0.04% carbon dioxide gas and a variable amount of water vapor.

Any physical body you can name, from aardvark to zyxomma, belongs to one of these three classes of substances that comprise the material universe. These are the raw materials with which the chemist works. Determining the composition of these bodies and learning about the changes which they undergo, as well as planning and controlling these changes and creating new compounds to give mankind a better and fuller tomorrow, is the business of modern chemistry.

2 Chemistry Uses Universal Symbols

CENTURIES before the first scientific definition of an element was formulated, and at a time when only a handful of chemical elements were known, a few restless and thoughtful men were pondering over the nature of matter. Was there such a thing as the smallest possible bit of matter? Could matter be divided indefinitely? Was a nugget of gold, for example, capable of being pounded into smaller and smaller bits indefinitely, or was there really a limit beyond which the last thin film or speck of gold could be divided before it would disappear or defy any further division? This theoretical question was evidently regarded as an important one by the big brains of ancient Greece and was kicked around for a long time by the best minds of those days.

Finally two different ideas about the nature of matter jelled. Anaxagoras, a celebrated teacher in Athens, insisted that all matter was continuous and, like numbers, was infinitely divisible. He had many followers. The great Aristotle, too, was a continuist. The other school of thought on this problem was led by Leucippus who lived in Miletus in Asia Minor about 2400 years ago, and by his pupil, Democritus of Abdera. These men insisted that matter was made up of very tiny, unbreakable, indivisible articles called atoms (meaning "cannot be cut"). This theory of atomism was essentially based on logical thinking about certain very limited observations, rather than on the evidence of any physical experimentation. No one of the followers of Democritus actually attempted to divide a bit of gold or copper into tinier and still tinier pieces to see what would happen to the final smallest speck. Yet these ancient philosophers saw fit to give a physical basis to this idea, which came to be known as the atomic theory of matter.

The Roman poet, Lucretius, took kindly to this theory and, being a crusader against ignorance, fuzzy thinking

and superstition, composed the world's greatest didactic poem in elegant verse entitled *De Rerum Natura* (On the Nature of Things). Here is a prose translation of part of this book written in 57 B.C.

"Now mark me: since I have taught that things cannot be born from nothing, cannot when begotten be brought back to nothing, that you may not haply begin to mistrust my words, because the first beginnings of things cannot be seen by the eyes, take moreover this list of bodies which you must yourself admit are in the number of things that cannot be seen.

"First of all the force of the wind when aroused beats on the harbors and whelms huge ships and scatters clouds. . . . Then again we perceive the different smells of things, yet never see them coming to our nostrils; nor do we behold heats nor can we observe cold with the eyes nor are we used to see voices. Yet all these things must consist of a bodily nature, since they are able to move the senses; for nothing but body can touch and be touched. Again, clothes hung up on a shore which waves break upon become moist, and then get dry if spread out in the sun. Yet it has not been seen in what way the moisture of the water has sunk into them nor again in what way this has been dispelled by heat. The moisture, therefore, is dispersed into small particles which the eyes are quite unable to see.

"Again, after the revolution of many suns [note the earth-centered concept of the solar system of the time] a ring on the finger is thinned on the under side by wearing, the dripping from the eaves hollows a stone, the bent ploughshare of iron imperceptibly decreases in the fields, and we behold the stone-paved streets worn down by the feet of the multitude; the brass statues, too, at the gates shew their right hands to be wasted by the touch of the numerous passersby who greet them. These things then we see are lessened, since they have been thus worn down; but what bodies depart at any given time the nature of vision has jealously shut out our seeing.

"Lastly, the bodies which time and nature add to things little by little, constraining them to grow in due measure no exertion of the eyesight can behold; and so, too, wherever things grow old by age and decay, and when rocks

hanging over the sea are eaten away by the gnawing salt spray, cannot see what they lose at any given moment. *Nature, therefore, works by unseen bodies.*"

So skillfully and lucidly did Lucretius state the case for the invisible yet ever-present atom that even had the ancients invented the microscope his case for the atomic theory could not have been strengthened. This simple notion of tiny, indivisible atoms of which all things are composed was gradually accepted even by the most cautious scientists. Sir Isaac Newton, who made his immortal contributions to science and mathematics during the seventeenth century, added his own great prestige to the acceptance of this theory when he wrote in his classic book, *Opticks*: "It seems probable to me that God in the beginning formed matter in solid, massy, hard, impenetrable, movable particles, so very hard as never to wear or break in pieces, no ordinary power being able to divide what God Himself made *One*, in the first creation."

This, the most fruitful of early Greek speculations, took on greater significance soon after the opening of the nineteenth century. It came through the mind and hand of a scarcely known, bookish, soft-spoken school teacher from Manchester, England. Not completely satisfied with the atom of Democritus which was based mainly on logical thinking, John Dalton announced his own atomic theory. It was rooted in some experimental observations; for example, on how invisible gases dissolve in water, and on other physical phenomena some of which later turned out to be quite irrelevant. The color-blind Quaker added something positive to the Greek model of the atom. Democritus had taught that all atoms, the atoms of fire and the atoms of water, were all alike, and that substances differed only because they were made up of different numbers of atoms. Dalton rejected this idea, and advanced the notion that the atoms of different elements differed in size, shape, and other properties. He explained that all the atoms of the *same element* were exactly alike, but that these atoms differed from element to element.

By proposing and carefully stressing the point that atoms of different elements had different weights which were constant for each element, he made a prodigious step

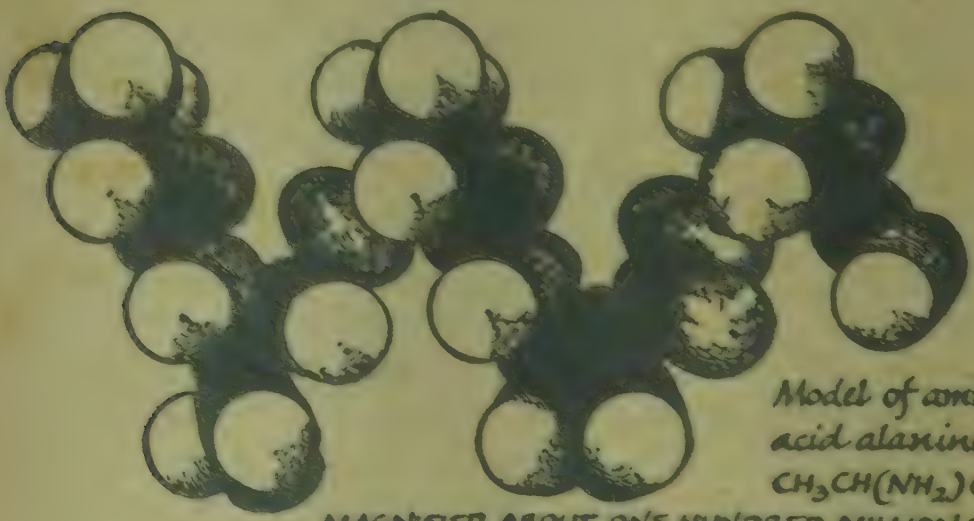
forward. He laid the foundation of chemistry as an exact and mathematical science. He said, for example, that all the atoms of the element hydrogen were the lightest atoms in existence and that the weight of a hydrogen atom was one-sixteenth that of the atom of the element oxygen. By assigning the hydrogen atom a weight of one, the atomic weight of oxygen became, of course, sixteen. The atomic weight of iron, following this system, became 56, that of gold 197, and that of uranium 238. These weights, it must be remembered, are only *relative weights*. Dalton had never weighed a single atom of any element. Even today, when we can determine experimentally the weight of any individual atom of any element, such weights are actually not used in chemical calculations because they are fantastically small. For instance, the weight of a single atom of even such a very heavy element as lead is only 0.000,000,000,000,000,000,000,336 gram! (There are 28.35 grams in one ounce.)

Dalton's first list of atomic weights, appended as a *Table of the Relative Weights of the Ultimate Particles,* was an historic document. Even though it comprised only a small fraction of the known elements and the figures were quite inaccurate, it proved immensely useful to the progress of chemistry. In the more than a century and a half since its publication tens of thousands of painstaking experiments with the most delicate, sensitive, and ingenious instruments have enabled chemists in many parts of the world to improve and refine the table to its present state. The current *Table of the Atomic Weights of the Chemical Elements*, which appears on page 217, is one of the keystones in the massive edifice of modern chemistry.

The teacher of science and mathematics in Manchester made another major contribution to our ideas about the nature of matter. He taught that during any chemical change it was the individual atoms of elements that either joined together to form chemical compounds, or, when combined in compounds, broke away from each other to liberate themselves as free and independent elements, or changed to simpler compounds.

Being a teacher of young people, Dalton understood the educational value of simple visual aids in the learning

process. He therefore constructed small spheres to repre sent individual atoms, and differentiated the atoms of dif ferent elements by different colors or markings on them For example, he represented the atom of carbon as a blac wooden sphere, oxygen as a white ball, and the hydroge atom as a smaller globe with a dot painted on its surface This simple device, modified and refined to indicate actua sizes, angles, and distances between atoms, and to mee the needs of an ever-increasing complexity of structure, i still used in laboratories and classrooms all over the world



Model of amino acid alanine chain $CH_3CH(NH_2)COOH$

MAGNIFIED ABOUT ONE HUNDRED MILLION TIMES

Dalton illustrated his notion of chemical union, for example, by explaining that when coal (or carbon) was burned in air, one carbon atom combined with either one or two oxygen atoms to form either one or two distinctly different chemical compounds named carbon monoxide and carbon dioxide:

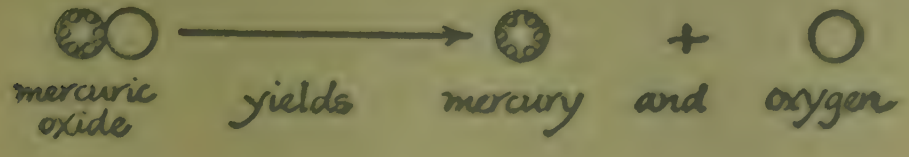
carbon + oxygen

(carbon monoxide, a very poisonous gas that may escape when a kerosene stove, for example, is improperly burning)

carbon + oxygen

(carbon dioxide, the gas that is dissolved in water to give club soda or Vichy water its pleasant taste)

Similarly, Dalton explained to his young students that when a red powder known as mercuric oxide is heated it breaks apart or *decomposes* into its two constituent elements, mercury and oxygen, thus:



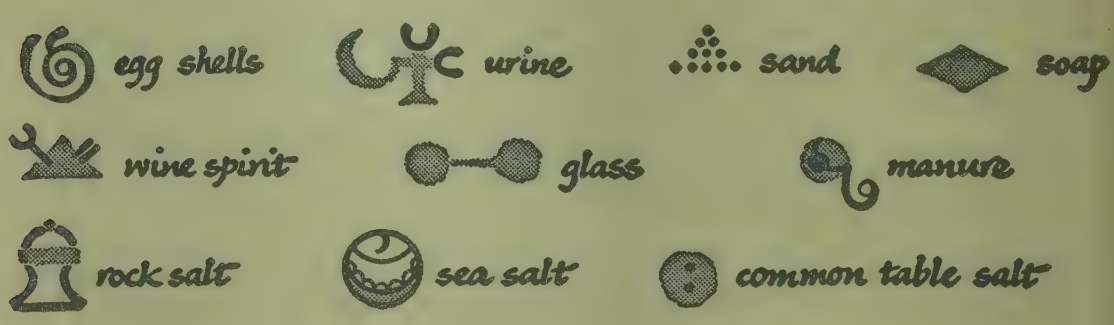
This simple and novel approach to an understanding of matter and the chemical changes which it undergoes should have taken the scientific world by storm. But it did not. When the rather shy and hesitating school teacher read the paper unveiling his new theory one evening in October, 1803, before "a select audience of nine members and friends in the Literary and Philosophical Society of Manchester" there was no favorable excitement visible. And the professional scientists and experts of his day were not impressed either. To be sure, Dalton had released his theory without benefit of press agent, or complete scientific confirmation. Soon almost all the scientific world was up in arms against it. Even some of the most eminent scientists of the great universities could not understand "how any man of science or sense would be taken up with such a tissue of absurdities." Dalton, they repeated, had actually never seen an atom, much less weighed one. He had admitted it!

Yet Dalton's little marbles and his whole atomic theory were eventually and universally accepted by his trade as a very useful working hypothesis, one of the temporary crutches of science to be discarded at some future time. Before the close of the nineteenth century, to be sure, new facts came to light destined not to force the complete abandonment of the theory but to revise and develop it drastically into a more rounded and more powerful tool. Dalton, as a matter of fact, had been wrong in most of his atomic assumptions, but his theory, in its own inadequate way, served chemistry faithfully for more than a century.

Dalton was not the first to use symbols to represent the chemical elements. The alchemists for hundreds of years

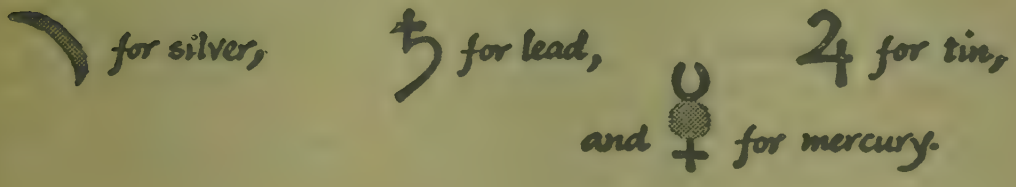
before him had employed a sort of picture shorthand. This breed of men (and a few women) of many countries and many centuries were some of the forerunners of the chemists of today. Alchemy helped to beget chemistry and reigned for more than two thousand years. The main goals of alchemy were two—to change the baser or cheaper metals such as lead and iron into the more noble and costly metals such as gold and silver, and to concoct an elixir of life, some mysterious liquid or philosopher's stone with powers great enough to cure all disease and prevent death. Although among these alchemists there were some honest enthusiasts, the annals of their secret practices are filled with the exploits of liars, crooks and charlatans. In several museums of Europe you can still see pieces of shiny yellow metal reputed to be gold, and made by the deceptions of some of the most infamous and clever "gold cooks" attached to European courts. Of course, many of these fakers were unmasked and some even ended on the gallows.

These alchemists tried hard to keep their "knowledge" secret and so surrounded their profession with a thick cloud of mystery. They were shrewd enough to know they would lose their unique position and prestige if their practice of alchemy became known to the people. Consequently they introduced strange symbols and puzzling signs, and only a handful of men could make even a little bit of sense out of the mysterious writings, which for a long time obscured the early history and beginnings of chemistry. They successfully buried their thoughts and distorted their prescriptions in a sign language which only they themselves understood. For example, here are some of the symbols:



They had accepted the circle as the symbol for perfection, so to them it also became the symbol of gold, most perfect of the metals.

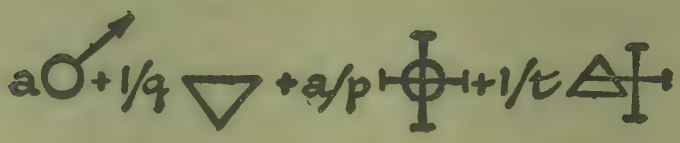
Some of the symbols found in alchemical manuscripts had been used in connection with ancient myths and legends. For example, the lance and shield of Mars represented by was the symbol of iron. The looking glass of Venus represented by the symbol stood for copper because, according to legend, Venus had risen fully formed from the sea foam on the shores of Cyprus, famous for centuries for its copper mines. The other four metals known to the ancients were represented by the following symbols.



To make things worse, the alchemists were not agreed among themselves on the choice of many symbols. As a result different alchemists used different symbols for the same substance. Furthermore, different symbols and different names were used by the same alchemist for the identical object. One Italian alchemical manuscript of the seventeenth century contains 20 entirely different pictures and 35 altogether different names for the same element mercury. This jungle of different symbols and mysterious names had to be cleared before an enduring system of chemical notation could be drawn up to make the study and advance of chemistry more widespread and rapid.

It was a long time before an international system of chemical shorthand could be agreed upon. Even as late as the opening of the eighteenth century Antoine Laurent Lavoisier, father of modern chemistry (that is, according to Frenchmen, for the Swedes regard their own Carl

Wilhelm Scheele, and the Russians their revered Mikhai Vasilievich Lomonosov as the founder of chemistry), was still using the following cumbersome and complicated symbols to represent a simple mixture of two elements and two simple chemical compounds:



The man who accomplished the monumental task of achieving universal acceptance of one single system was the Swedish chemist, John Jacob Berzelius. His plan was really a very simple one. "It is easier," he suggested, "to write an abbreviated word than to draw a figure which has little analogy with words, and which to be legible must be made of a larger size than our ordinary writing. . . . The chemical signs," he pleaded, "ought to be letters for the greater facility of writing, and not to disfigure a printed book. I shall, therefore, take for the chemical sign the initial letter of the Latin (or common) name of each chemical element."

Thus the element carbon was assigned the symbol C, hydrogen H, oxygen O, nitrogen N, phosphorus P, sulfur S, and so on. "If the first letter" he added, "be common to two or more elements I shall use both the initial letter and the first letter they have not in common." Thus we have:

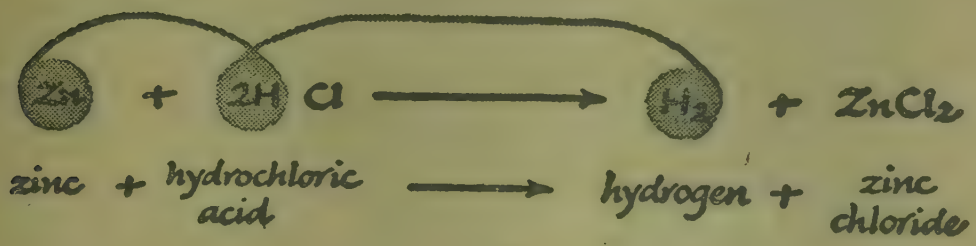
ELEMENT	SYMBOL
COPPER	Cu (*Latin cuprum*)
COBALT	Co (*Latin cobaltum*)
CALCIUM	Ca (*Latin calx*)
CHROMIUM	Cr (*Greek chrom*)
POTASSIUM	K (*Latin kalium*)
KRYPTON . .	Kr (*Greek kryptos*)
ANTIMONY	Sb (*Latin stibium*)
TIN	Sn (*Latin stannum*)
SILICON	Si (*Latin silex*)
SELENIUM	Se (*Greek selene*)

with new characteristics takes their place. The white powder formed is a compound of the two elements and is called zinc sulfide (ZnS).

The chemist expresses this chemical change by a chemical shorthand called a chemical equation, thus:

$$Zn + S \longrightarrow ZnS$$ (The arrow signifies "forms")

This is, of course, a very simple equation. Now let us consider one which is somewhat more complicated. When, for example, a piece of the element zinc is placed in some hydrochloric acid, a gas is liberated, heat is evolved, and a white powder may be extracted after the action. The gas evolved is hydrogen gas, and the white powder is zinc chloride, a compound of zinc and chlorine. Hydrochloric acid is a compound of hydrogen and chlorine. The equation for this chemical event is written as:

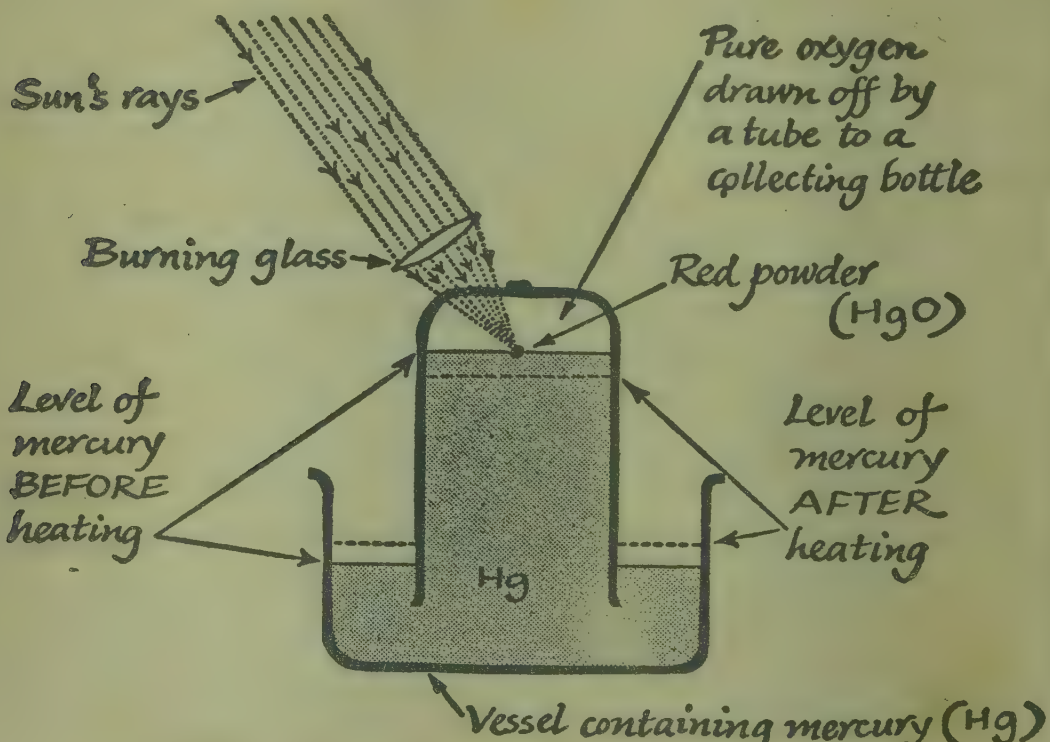


By inspection you can see that in the above chemical change the element zinc has replaced the element hydrogen in the hydrochloric acid and changed the latter into zinc chloride. The zinc disappeared as a free or uncombined element and was replaced by free hydrogen gas. The invention of this symbolism in equations was a significant advance in the study of chemistry.

Now you are probably asking yourself at least two questions. First, why does the chemist place a 2 in front of HCl, and what does it signify? Second, how does he know what subscript to use—the 2, for example, in $ZnCl_2$? To answer these questions I must first mention a generalization in chemistry which is basic to a study of all science. It was discovered by Lavoisier and by at least

two other scientists at about the same time. It is know as the Law of the Conservation of Matter. In its simple form the law states that one cannot create something o of nothing, and that one cannot completely destroy an thing. All we can do even in the most violent chemic change is to convert one form of matter into some oth form of matter.

To illustrate, on Sunday, the first of August, 177 Joseph Priestley, one of the greatest amateur chemists all time, heated a red powder known to the Arab schol Geber and other alchemists as *mercurus calcinatus per s* He wanted to see if he could extract some gas from Until his time, the various gases had been studied b collecting them first in balloon-like bladders. This was very clumsy method, and besides the bladders were no transparent. Priestley developed and introduced the simpl modern method of collecting gases. He filled a glass bottl with mercury and inverted it over a larger vessel of mer cury so that the mouth of the bottle was below the quick silver in the vessel. A glass delivery tube was connecte (frequently by means of a cork) to a glass flask in whic the gas was being generated, and the end of the deliver tube was placed under the mouth of the bottle of mercury


Sun's rays
Pure oxygen drawn off by a tube to a collecting bottle
Burning glass
Red powder (HgO)
Level of mercury BEFORE heating
Level of mercury AFTER heating
Hg
Vessel containing mercury (Hg)

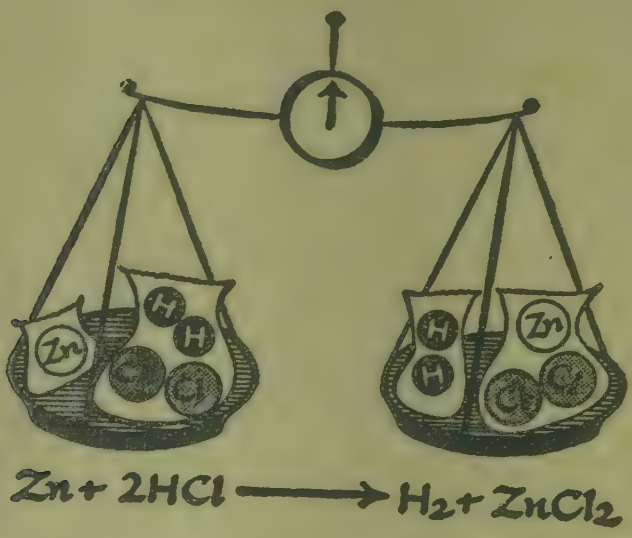
The escaping gas displaced the mercury in the bottle, and was thus imprisoned in a strong, transparent container.

As a source of heat for the experiment he used that of the sun's rays concentrated by a huge sunglass with a lens a foot in diameter. After heating the red powder in this way he reported that "I presently found that air was expelled from it readily." A lighted candle was burning in his laboratory. He wondered what effect this gas might have on the flame of the candle. Merely as a chance experiment, he inserted the candle in the gas. The flame was not extinguished. Furthermore, he wrote, "what surprised me more than I can well express was that it burned with a remarkable vigorous flame . . . I was utterly at a loss to account for it." Priestley had discovered pure oxygen, which had been released by the heat from the compound mercuric oxide.

Now Lavoisier, soon after, repeated this experiment that immortalized the English minister, but did it with even greater precision. He bought some mercuric oxide from the same Parisian apothecary that had supplied Priestley, and possibly it even came out of the same bottle. He weighed the red powder very carefully with the most delicate chemical balance in all France. He weighed also the oxygen gas liberated as well as the mercury left after the chemical reaction was complete. He found that the combined weight of mercury and oxygen was exactly equal to the weight of the mercuric oxide which had "disappeared" during the heating . . . no more and no less.

Now we are ready to tackle the first question mentioned on page 31. If we start with a definite number of atoms of zinc, a certain number of atoms of hydrogen, and a weighed amount of atoms of chlorine, these same numbers obviously must show up after the chemical change, though not necessarily in the same bodies in which they were originally used. To conform to this situation—that is, for this chemical change not to violate the universal Law of the Conservation of Matter—the chemist juggles the numbers in front of formulas of compounds or symbols of elements (coefficients, we call these numbers) until this state of affairs is reached. Thus, by placing the coefficient

2 in front of HCl we account for the two atoms of H and the two atoms of Cl on the right side of the arrow in the equation. The formula $ZnCl_2$ takes care of the two atoms of chlorine and the H_2, which represents a molecule of free hydrogen gas, takes care of the two atoms of hydrogen. To sum up, we now have two atoms of hydrogen on each side, 2 atoms of chlorine on each side, and 1 atom of zinc on each side of the arrow, and the equation is said to be chemically *balanced.*



This fixing of the proper coefficients in an equation is called balancing an equation. No chemical equation is mathematically correct until it has been properly balanced.

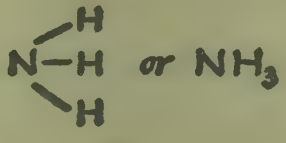
In connection with this same equation you may have wondered why hydrogen is written with a subscript 2, whereas zinc is not so shown. Without embarking on a long and somewhat complicated story let it be said that certain elements, notably some common gases such as hydrogen, oxygen, nitrogen, and chlorine, when they occur uncombined and as free elements, exist as pairs of atoms—that is, two atoms are attached to each other in a single molecule of the gas to form a diatomic or twin molecule.

The second question mentioned above is even more involved. Why does the chlorine in the molecule of zinc chloride have a subscript 2? Why is not the formula of zinc chloride simply ZnCl? The answer lies in the concept of *valence*. This concept was introduced in 1852 by an

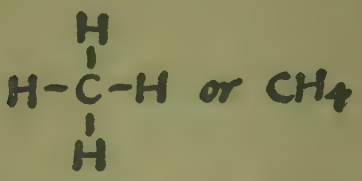
English professor of chemistry at Manchester, Sir Edward Frankland, and sixteen years later the name valence was suggested by another chemist.

It was known that elements occur in different numbers of atoms in different chemical compounds. For example, a molecule of hydrochloric acid contains one atom each of hydrogen and chlorine and is written HCl. The molecule of hydrogen sulfide gas oozing out of stagnant pools, and more swiftly propelled from rotten eggs, contains two atoms of hydrogen and one of sulfur. Its formula is H_2S. In the compound called ammonia gas, which when dissolved in water is the familiar household cleaning agent, there are three atoms of hydrogen and only one of nitrogen. Its formula is NH_3. Finally, the main constituent of natural gas so widely used in cooking and heating is a compound whose formula is CH_4. This molecule contains 4 atoms of hydrogen and again only one atom of carbon.

Frankland, in an effort to explain this phenomenon, proposed that each element had its own characteristic valence, that is, a tendency to unite with one or more atoms of hydrogen. Hydrogen itself had a valence of one. It is univalent, has a single valence bond—only one hand, so to speak, and can hold on to the one hand of some other one-handed element such as chlorine to form hydrochloric acid (HCl). Oxygen is different. It is two-handed (divalent) and can, therefore, latch on to two separate single-handed hydrogen atoms to form H-O-H or H_2O. Similarly, a nitrogen atom is a curious three-handed creature that can hold on to the single hands of three one-handed hydrogen atoms at the same time to produce



Finally, carbon is not quite an octopus but does possess four hands and with them clings to four hydrogen atoms to make a molecule of



Also one divalent element such as zinc can combine with only one other divalent element such as oxygen to form a molecule of Zn=O or ZnO (zinc oxide).

This was in a sense a naïve explanation, but it served its purpose for a half a century, when a brilliant shower of new discoveries presented a truer and more sophisticated picture of chemical valence. This new explanation will be discussed in a later chapter.

3 Simple Kitchen Chemistry

WITH the foregoing capsule of basic information let us take a look around the kitchen. Even the most modest kitchen is the storehouse of some of the most important classes of chemical compounds, and the laboratory of some of the commonest chemical reactions to be found in the mighty tomes resting in chemical libraries. If you understood thoroughly the chemistry of your kitchen you would indeed be a tolerably good chemist.

Let us consider a few of these chemicals. Of course, we ought to begin with that omnipresent and omnipotent liquid which pours forth at the turn of the faucet. Any high school boy or girl could tell you at once that this is a compound and that its formlua is H_2O. Yet as late as the close of the eighteenth century this commonest of all liquids, this universal solvent, was thought to be an element, as the most learned men had believed for centuries. Its composition had for so long eluded the early scientists (or natural philosophers, as they were called) for a very good reason. No one had been able to break it apart into simpler substances. Even the most violent boiling produced only water vapor or steam, both of which returned to the colorless liquid state upon cooling. Several early investigators brushed very close to disproving the elementary nature of water, but it was left to one of the most unusual characters in the whole history of science to hit upon the crucial test.

This was the Englishman, Henry Cavendish, born in 1731 to Lady Anne Cavendish, who had gone to France in search of health. In spite of an immense fortune left to him by his father, which made him the richest man in England, he lived a long, quiet, solitary bachelor life in the family mansion with but one single, all-consuming passion—scientific research. Despite his great wealth he lived very frugally, wore the hand-me-downs of his father

and very seldom dipped into the millions kept for him in the Bank of England.

In his early forties he made one of his many classic discoveries. He tossed some iron into a flask containing hydrochloric acid, collected the invisible gas that bubbled up, and for the first time in history accurately described the odorless, inflammable gas now known as hydrogen. This is the element that later was used first to inflate balloons and dirigibles, and in turn was almost completely superseded by another gas, helium, somewhat heavier than hydrogen but safe from explosions because it will not catch fire under any conditions. Hydrogen, too, when passed through such vegetable oils as cottonseed oil combines chemically with them to give us a new compound—a hydrogenated shortening such as Crisco, Spry and oleomargarine.

A few years later this same superb experimenter tried passing an electric spark through a mixture of his newly discovered gas and the element oxygen—the gas which Priestley had isolated and described for the first time. Cavendish had a hunch suggested by some of the work of his contemporaries. He repeated this experiment several times using a sealed flask, breaking many a bottle as he boldly sparked explosive mixtures of hydrogen and oxygen. He checked every move and every observation. Here was an error which he had not noticed before. He must dry his gases thoroughly to make sure no moisture was present in either of them. He did the experiments over again with perfectly dry gases. Where the ordinary investigator might detect one flaw, Cavendish uncovered two and even three. Then as the figures and computations filled page after page of his notebooks, all of his results began to check. Now after many long months of labor he was ready to make his discovery public. But he waited for additional data. Had he not delayed so long, however, he would have prevented a controversy in the world of science which lasted almost half a hundred years.

Before the spring of 1783 he made known the results of these experiments to his friend Priestley. Three months later, Lavoisier, too, was notified in France. But the year 1783 went by and Cavendish still waited to publish his

results. Like Charles Darwin many years later, he displayed none of the itch to rush into print that so generally follows some important discovery. Not until January, 1784, did he finally read his paper on "Experiments on Air" before the most distinguished body of British scientists, the Royal Society of England.

And this is what he told that critical audience. He had found water to be a compound of two gases, hydrogen and oxygen, in the ratio of two volumes of hydrogen to one volume of oxygen. That clear, life-sustaining, limpid liquid was not the simple elementary substance all the savants of the world thought it to be. It was not an element. It was, in fact, H_2O. The mystic power of chemistry had fashioned it out of two invisible gases!

But how could he be absolutely certain that it was water that formed in the flask after the explosion? They were sure to ask this question. He had to prove it to them. He went to the trouble of burning enormous volumes of pure hydrogen and air and then condensed a good deal of "water which had no taste or smell and left nothing behind when evaporated to dryness, neither did it yield any smell during the evaporation. In short," he wrote down in his notebook, "it seemed pure water." Positive-enough experiments, tests that were infallible, and yet Cavendish would only report, "it seemed." Was he afraid his listeners would not be convinced? Water, a compound of two gases? Incredible!

Cavendish went further. If it was only the oxygen of the air which combined with his hydrogen, then there should be left behind after the sparking four-fifths of the original volume of air used, since air contained approximately 20% of oxygen by volume. The remaining gas should be another colorless gas, nitrogen, which had already been discovered by a scientist named Daniel Rutherford, uncle of Sir Walter Scott, the great novelist. This nitrogen gas should not be capable of being burned and could not support breathing, and mice should not be able to survive very long if imprisoned in it. So Cavendish tested the gas very carefully on every one of these counts. It was really nothing but nitrogen by every test he tried.

That was not the end of it. The Frenchman, Lavoisier,

performed another experiment that silenced even the most skeptical scientist. Cavendish, as we have just described, built up or synthesized pure water out of its elements. Lavoisier reversed the act. He broke down or analyzed pure water into its two constituent elements by an ingenious experiment. He passed water in the form of steam over red-hot charcoal or carbon. Two gases were formed and nothing else. One was hydrogen and the other was carbon dioxide. The carbon, he reasoned, had torn away the oxygen in the water molecule to form carbon dioxide, liberating the other element originally present in water, namely hydrogen. The chemical equation representing this chemical change may be expressed as follows:

$$2H_2O + C \longrightarrow CO_2 + 2H_2$$

steam + carbon ⟶ carbon dioxide + hydrogen

James Watt, the famous inventor and developer of the steam engine, had also been interested in this problem and had done some experiments of his own at about this time. He wrote to Priestley about his findings and then transmitted a report to the Royal Society claiming discovery of the composition of water eight months before Cavendish had addressed the same body. Lavoisier, too, believed he was entitled to recognition for this discovery on the basis of an oral report he had submitted to the French Academy of Sciences even earlier than Watt's alleged report. Even Priestley was tempted to get into the act on his own behalf but, favoring Watt, remained on the sidelines watching the sparks fly in this historic battle. Cavendish, as you might have expected, refused to become embroiled and took no part in the intellectual hassle.

Now let us get back to some of the other chemicals in the kitchen. There may be a bottle of sour milk in the refrigerator, perhaps some vinegar, a few lemons or grapefruit, too. In spite of the very obvious differences among the items just mentioned they do have something in common. They all contain acids. This word is derived from the Latin *acidus*, meaning sour. Even though the taste re-

actions of people towards different chemicals vary widely, nearly everybody will find the taste of what the chemist defines as an acid definitely sour. All acids also possess another property in common. They will change a piece of white blotting paper dipped in blue litmus (a coloring matter extracted from a lichen plant) from blue to pink when in contact with it.

Furthermore, the molecules of all acids contain one or more atoms of hydrogen. Thus, the formula of acetic acid, which becomes vinegar when much water is added to it, is $H.C_2H_3O_2$; the formula of carbonic acid, which is found dissolved in many beverages such as club soda, vichy, and soda water, is H_2CO_3; that of boric acid, occasionally used as an eyewash, is H_3BO_3. Citric acid is found in lemons and grapefruit and used to impart flavors to carbonated beverages, jams, pastries and dessert powders. Lactic acid is present in sour milk, and hydrochloric acid is found to a small extent (about 0.3%), in the stomach's gastric juice, where it helps in the digestion of foods. It is also present in muriatic acid, used to clean rust spots in washbowls.

The hydrogen found in acids is a special kind of hydrogen. It is hydrogen that can be replaced by some metals. When, for example, zinc is added to vinegar a chemical change takes place, during which one zinc atom replaces two hydrogen atoms of acetic acid. These two hydrogen atoms which are formed are liberated as a molecule of hydrogen gas, and a new chemical called zinc acetate is left behind. The balanced equation for this reaction is:

$$Zn + 2H.C_2H_3O_2 \longrightarrow H_2 + Zn(C_2H_3O_2)_2$$

zinc + acetic acid ⟶ hydrogen + zinc acetate

where the acetate group, $C_2H_3O_2$, is called a radical, that is, a group of atoms that acts as a single atom.

Similarly, when a strip of magnesium metal is dropped into a glass of lemon juice, the citric acid present in the lemon is changed to magnesium citrate when the hydrogen of the citric acid is replaced by the magnesium atom.

Magnesium citrate is the main active ingredient of ci of magnesia used as a laxative.

It must be mentioned that there are tens of thousa of compounds containing hydrogen which are not ac This is because the hydrogen atoms present in their m cules cannot be replaced by metals. Or to put it n scientifically, such chemicals as sugar, starch, gasol mineral oil, and chloroform, all of which contain hyd gen *atoms* in their structures, do not contain hydro *ions*. A hydrogen ion differs from a hydrogen atom in t the former is a positively charged particle while the hyd gen atom is electrically neutral.

When an acid dissolves in water, its molecules br apart or dissociate, forming two electrically charged p ticles called *ions*. Thus HCl forms one hydrogen (H+) and one chlorine ion which carries a negative cha (Cl−). Hydrogen ions are always formed when ac dissociate, and it is the hydrogen ion that gives the a all of its typical acid properties mentioned above. It responsible, for example, for the sour taste of the ac Moreover, the more hydrogen ions an acid forms, t stronger is that acid. For example, vinegar (acetic aci dissociates very slightly and forms only a few hydrog ions. It is, therefore, a very much weaker acid than, sa hydrochloric acid, which dissociates completely in wat forming huge numbers of hydrogen ions. That is why is perfectly safe to use vinegar in seasoning food, where no one in his right mind has ever knowingly tried to u hydrochloric acid for this purpose. It is altogether t strong both in taste and in its burning effect on the tissu of the mouth.

In your kitchen or nearby bathroom you may also fi a bottle of ammonia water (NH_4OH) used for cleanin You may also discover a can of lye which is composed impure sodium hydroxide (NaOH). This "caustic sod is a useful household cleansing agent because it dissolv or cuts grease. When kitchen or bathroom plumbing b comes clogged, a strong water solution of lye is poure down the pipes. In this way greasy, fatty accumulatio are reacted upon by the lye (saponified) and as a resu of this chemical change become soluble in water. Drā

and other common plumbing cleaners sold under various trademarks all contain this chemical.

Many fruits and vegetables are peeled before canning by the use of a 20% sodium hydroxide solution in which they are immersed for from two to five minutes. The sodium hydroxide attacks the pectins or binding materials between the cells, loosening the skins. These are then removed by washing, which also removes all traces of the lye from the fruit. This process is an outgrowth of the making of old-fashioned lye-hominy, a staple in the diet of the early American colonists. In the making of lye-hominy, grains of corn were soaked in a lye solution until the hard, tough skin of the corn grain became loosened. Pure lye or even fairly dilute lye solutions produce painful and serious burns if they come in contact with the skin. They should be used with great care and stored out of the reach of small children.

Milk of magnesia may also be found in your medicine chest. This is a suspension in water of magnesium hydroxide [$Mg(OH)_2$], which acts as a mild laxative. Milk of lime or limewater [$Ca(OH)_2$], too may be among the chemicals in your medicine chest. This is a household medicine that corrects acid stomach. (Incidentally, its chemical composition is the same as that of whitewash and hydrated lime!)

All of these substances just described belong to a second class of compounds known as bases or alkalies. All of them have a number of characteristics in common. They are all bitter to the taste, caustic to the skin, soapy to the touch, and turn litmus from pink to blue. All of the common properties that they possess are due to a combination of the hydrogen and oxygen atoms which they all contain. This combination of elements is called the OH or hydroxide group or radical. Again, to be more accurate, we should say that all bases owe their common characteristics to the presence usually of the hydroxide ion—that is, the OH group carrying a negative charge (OH^-). The more numerous the hydroxide ions produced by a base, the stronger is that base. There may be other chemicals around the house which contain the OH group, such as

grain alcohol (C_2H_5OH) but these do not form the C ion and therefore are not bases.

Most common compounds belong to one of three classe two of which, the acids and the bases, have just be described. The other main class of chemical compoun comprise the salts. A salt is any compound formed wh the hydrogen of an acid is replaced by a metal. When w ordinarily speak of salt we refer to common table sa This particular salt may be formed by replacing the H HCl (hydrochloric acid) by the metal Na or sodium. Th formula of table salt or sodium chloride, therefore, NaCl.

Another salt that may be found in your home is wash ing soda or sodium carbonate, Na_2CO_3. This is the sodiu salt of carbonic acid, H_2CO_3. Epsom salt, a laxative, is th salt of sulfuric acid (H_2SO_4) whose hydrogen has been re placed by the metal magnesium, and whose formula i therefore, $MgSO_4$. Sodium glutamate, which intensifie the distinctive flavors of many foods, and was known fo centuries in an impure form by Orientals, is the sodiu salt of glutamic acid.

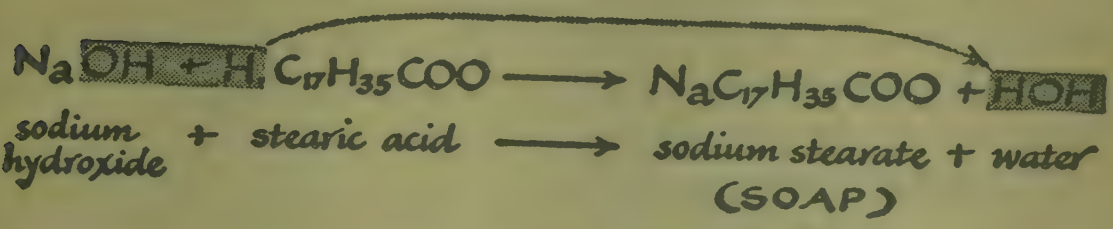
Baking powder contains a mixture of two salts. One o these is always sodium bicarbonate (bicarbonate of soda which is another sodium salt of carbonic acid. The othe ingredient of baking powder may be potassium acid tar trate ($KHC_4H_4O_6$), which is the potassium salt of tartari acid ($H_2C_4H_4O_6$) found in grapes. When these tw white powders come in contact with water, a chemica reaction takes place during which carbon dioxide gas i formed. Bubbles of this harmless gas remain to give the bread or cake a soft, porous consistency.

The white shells of the eggs you use are composed of a chemical known as calcium carbonate. Hens get this cal cium carbonate in the form of oyster-shell or grit in thei diet. Chemically, it is the same stuff that constitutes lime stone for building, marble for statues, chalk for writing as well as pearls, coral, and glassy transparent calcite Calcium carbonate is the second most widely distributed mineral on earth, making up an important part of the rock in many of our mightiest mountains. But to the chemist it is just another salt, the calcium salt of carbonic acid. Still

another salt that may be found around the house is aluminum chloride ($AlCl_3$), the aluminum salt of hydrochloric acid. Aluminum chloride is a chemical ingredient of many deodorants and antiperspirants.

Good old-fashioned soap is also a salt. It is usually the sodium salt of acids derived from animal or vegetable oils or fats. Soap is manufactured by adding sodium hydroxide, a strong base, to an acid such as stearic acid found both in beef fat and in olive oil. The acid and base react when heated, forming soap, and glycerine is formed as a by-product.

The chemical reaction known as saponification may be represented as:



Soap is not a modern invention. In ancient Babylon the most commonly used chemicals for washing both body and clothes were impure sodium carbonate (Na_2CO_3) and potassium carbonate (K_2CO_3). The first, called soda ash, was obtained by leaching—that is, passing water through the ashes of seaweeds and other plants growing inland near salt water. Land plants and wood (oak) treated in the same way supplied K_2CO_3 or potash. Both of these salts are alkaline—a word derived from the Arabic *al* (the) and *kali* (ashes). The Gauls prepared a form of soap from tallow and wood ashes as early as the second century.

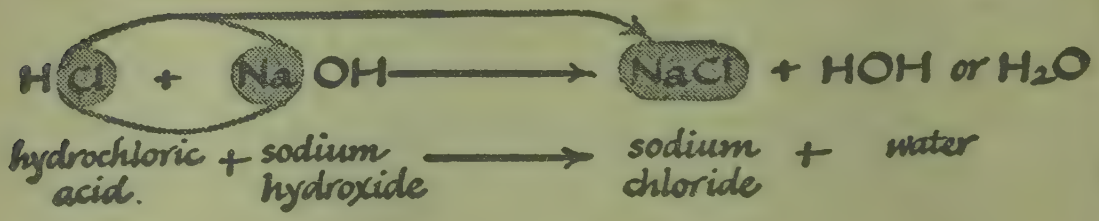
The first potash for soapmaking produced in this country was made by eight Poles and Germans sent over here by the London Company. By 1788 the number of potash works in Massachusetts alone was 250. It took 700 bushels of field or fireplace ashes to make one ton of potash, worth at that time $120. More than half of the expense of clearing new land in New York in those days was repaid by the proceeds of the potash obtained by

burning the wood. Potash was extracted in huge iron pots The first United States patent ever issued was granted by the Government over the signatures of George Washington and Thomas Jefferson for a new process for making potash, invented by a Samuel Hopkins of Burlington Vermont, in 1790.

Sumerian tablets dating back to 2250 B.C. contain recipes for the preparation of a crude soap from wood ashes and oils. Every housewife in Colonial days was her own soapmaker. She obtained lye by leaching the wood ashes from her open fireplace and used the suet from her cooking. A better grade of soap was sometimes made by using the oil pressed from bayberries.

You can easily realize that there must be many more salts than there are acids, and hundreds of acids have already been identified. Furthermore, every one of the more than 70 different metals known to the chemist can replace one or more of the hydrogen present in many of these acids. Salts are closely related not only to acids but to bases as well. For example, salts are the products formed when an acid reacts chemically with a base. To illustrate, when hydrochloric acid (HCl) is added to sodium hydroxide (NaOH) a curious reaction takes place. The hydrogen ion of the acid seeks out the hydroxide ion of the base, combines with it and forms HOH or H_2O—that is, chemically pure water. This is a deepseated change. Remember it is the hydrogen ion of the acid that gives the acid its sour taste and all the other properties characteristic of acids, while the hydroxide ion of the base is responsible for the soapy touch and caustic action of the base. Now both of these ions have been destroyed when they united to form common water. The acid is said to have neutralized the base, and vice versa.

This type of chemical reaction is called neutralization. The following equation may be written to express it:



Note that in the above equation a salt has also been formed by the union of the metal sodium of the base and the nonmetal chlorine of the acid. A similar salt formation occurs in every neutralization reaction.

Neutralization is a very useful process. For example, if you happen to be a farmer whose soil is slightly acid in character and you want to plant potatoes (which thrive best in a soil that is neutral) you will probably neutralize the soil by adding a mild base such as calcium hydroxide. This will react with the soil acid, remove sourness and sweeten the soil. Eighty per cent of the cultivated land in the central west of our country is sour. It is neutralized by the addition of lime (CaO) or limestone and oyster shells ($CaCO_3$). Or, if your dentist finds your mouth is more acid than it normally should be he will prescribe some toothpaste containing a mild base or antacid such as magnesium hydroxide, or some mouthwash containing the same or similar compounds. Or, again, if you were accidentally to get some strong acid on your clothes, you could prevent a nasty hole or burn by quickly applying some ammonia water which would neutralize the action of the acid.

Normal healthy blood is slightly akaline or basic. *Alkaline reserve* refers to the amount of base present as bicarbonate in the blood. Even slight changes in the normal alkaline condition of the blood result in serious body disturbances. Such disturbances may in many cases be corrected by using neutralizing chemicals administered by a physician. Existence of an alkaline reserve (a scientific fact) is, unfortunately, used by some advertisers as a reason for selling to the public huge quantities of alkalizers to dose ailments that are best treated by altogether different methods administered by physicians. Unfortunately, neither a sour disposition nor a caustic tongue will respond to such a relatively simple treatment. The chemistry of these two states is altogether too complex for such a direct remedy.

Before we leave the kitchen we were visiting, let us discuss the chemistry of the flame burning on the kitchen range. Burning remained a mystery from the moment when early man first discovered how to use fire up to

comparatively recent days. About 300 years ago a German scientist advanced the theory that all burnable substances contained *phlogiston* or "fire-stuff." He said that when a substance burned, *phlogiston* left in the form of a flame. He believed that the ash that remained after a substance had burned was the same substance minus this phlogiston. According to this theory, substances that burn readily (such as gasoline) contain a great deal of phlogiston and leave little or no ash behind. On the other hand, substances that burn with difficulty (such as tin) contain little phlogiston and leave a great deal of ash behind. The phlogiston theory was the first broad theory of the science of chemistry.

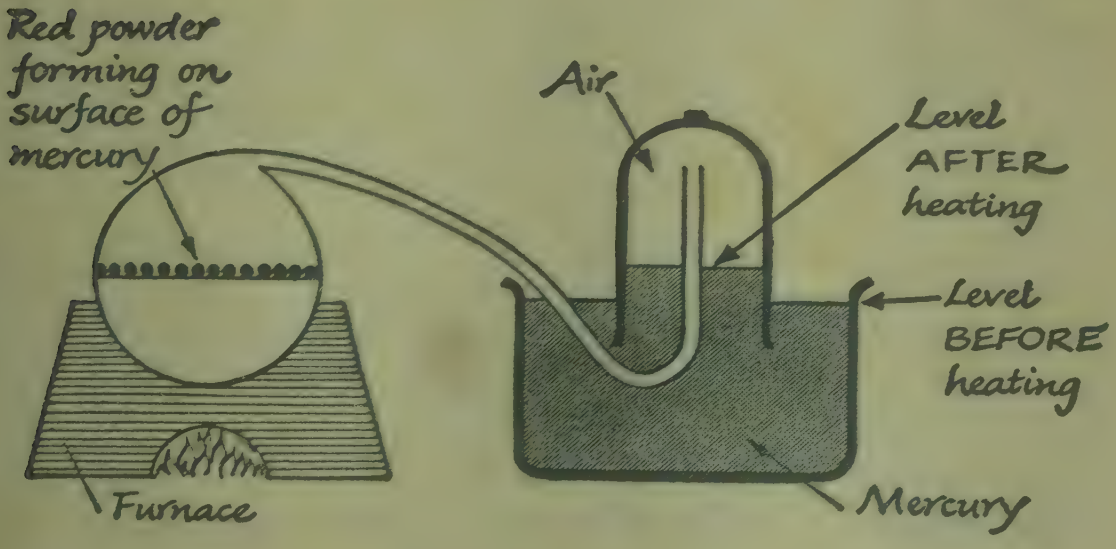
It seemed a correct explanation because of certain observations that had been made. A rising candle flame, for example, seems to tug at the wick. This suggested the idea that phlogiston was escaping from the burning candle. When a small amount of powdered lead was heated in an iron spoon it was seen to melt, burn, and form a yellow powder. According to the phlogistonists, this lead powder is lead ash—or lead minus its phlogiston. Now, if some way could be found to add some phlogiston to this lead ash, lead should be produced again. Perhaps this could be done by heating the lead ash in some substance that was rich in phlogiston, such as charcoal. When this experiment was tried, the final product was indeed found to be lead. This and similar crude experiments seemed to prove the correctness of the phlogiston theory.

But the explanation was all wrong. It was as false as alchemy. The theory finally was crushed on the rock of simple observation; namely, that substances, during burning, gained weight instead of losing weight when their so-called phlogiston escaped in the flame of the burning. This was tied to another clue—the notion that air had something to do with it. Leonardo da Vinci, the great Italian genius of the fifteenth century, left a large number of notebooks. In one of them may be found two relevant remarks. "The element fire," he wrote, "continuously consumes the air as concerns that portion which nourishes it, and a vacuum would be formed if other air did not come to supply

its place." "Where flame cannot live," he noted in another place, "no animal that draws breath can live."

Lavoisier almost three hundred years later, possibly even without knowing what da Vinci had recorded, wondered why it was that certain elements that he had heated, notably phosphorus and sulfur, increased in weight. A few years later when Priestley told him about his discovery of oxygen the solution to the age-old puzzle of burning seemed to be at hand. The French scientist suspected that this increase in weight when a substance burned was due to the union of the burning substance with the gas present in air that Priestley had just announced. Lavoisier proceeded to perform what turned out to be his classic 12-day experiment.

"I introduced four ounces of pure mercury," he wrote, "into a sealed glass vessel. I lighted a fire in the furnace which I kept up continuously for twelve days. Small red particles began to appear on the surface of the mercury." When most of the liquid mercury had been converted into the red powder he removed the glass vessel and its contents (which he had weighed before the experiment) and weighed them again. There was *no increase* in weight. Since the glass vessel was sealed, nothing had either entered or escaped from it during the heating. Yet when he carefully broke the seal of the glass he noticed that air rushed into the vessel. To him this indicated that part of the air in the vessel had been used up during the heating,



and had left space for more air to enter. After air had entered, he weighed the vessel once more and determined the exact increase in weight. He found that this increase in weight exactly equaled the weight of something in the air in the vessel that must have combined with the mercury to form the red powder.

Then he shrewdly reversed the experiment. He heated the red powder to an even higher temperature as Priestley had done before him, and carefully collected all the mercury and all the colorless gas that resulted. He tested the gas that he had trapped in a glass container and found it to be pure oxygen. He concluded, therefore, that it was the oxygen in the air that was responsible for burning. Burning, said Lavoisier, is the rapid chemical union of a substance with oxygen. Simple enough. No mysterious phlogiston—and the most sensitive weighing device in all of Europe to support his reasoning.

To come back to the flame burning on your kitchen gas range. If it is water gas* that is burning, then the chemical reaction may be represented as

$$CO + H_2 + O_2 \longrightarrow CO_2 + H_2O$$

carbon monoxide + hydrogen gas + oxygen of the air ⟶ carbon dioxide + water vapor

* Water gas made from coal is a mixture of carbon monoxide and hydrogen.

The delicate glow of the firefly that darts about in the night like a will-o'-the-wisp and the roaring flame of a volcano in eruption are the same chemical reactions. The slow, unnoticed silent rusting of a bit of iron is the same chemical change of oxidation, except that no light is observed and the heat liberated cannot easily be detected because the process is so slow and all the heat is dissipated over a long period of time. Similarly, respiration is an oxidation as Lavoisier first showed, declaring that "life itself is a chemical function."

With the successful unravelling of the mystery of fire

and the introduction of Dalton's atoms and Berzelius' symbols, alchemy might be said to have finally died. Modern chemistry was born.

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4 New Medicines for Mankind

DURING the fifty years that followed the discovery of oxygen, progress in chemistry was rapid and widespread. Chemistry changed from a purely descriptive to a truly physical science with underlying laws and principles. Its mathematical basis was firmly established; new elements such as wolfram, titanium, and chromium, were discovered, and thousands of new compounds were introduced. Salts and other chemicals were manufactured in large quantities, including a few of the compounds either discovered or used by the alchemists, such as nitric and sulfuric acids.

One branch of chemistry, however, continued to stagnate—the chemistry of the products of living things. Organic chemistry, as this field of chemistry is called, was strait-jacketed by the notion that the chemist could never hope to gain mastery over this kind of chemistry. Compounds made by the living plant or animal, he was told, could be made only by the living organism. Inside the pulsating cells of plants and animals, it was believed, burned a steady, invisible flame, and through this flame a mysterious *vital force* built up the sugars, the starches, the fats, the proteins, and the hundreds of other very complex compounds.

This extremely vague creative force was found only in the animal and vegetable kingdoms and never in the mineral world. "Nothing but the texture of living vegetables, nothing but their vegetating organs, could form the matter extracted from them; and no instrument invented by art could imitate the compositions which are found in the organic machines of plants." Man could never imitate the power of this vital force. It was, everybody believed, one of those mystic agencies of which man was destined to remain in ignorance all the days of his life. Some actually doubted whether such organic compounds even obeyed the established laws of inanimate or inorganic chemistry.

Such was the prevailing opinion in 1828 when a young

German chemist, still in his twenties, exploded this myth in a Berlin laboratory. He had just returned from a visit to Berzelius in Sweden. Berzelius, too, had spoken to him of the impassable gulf which separated organic compounds from inorganic chemicals. Young Friedrich Woehler had serious doubts, however, about this point of view. He kept thinking of the words of an eminent French chemist, Michel Chevreul: "To regard this distinction as absolute and invariable would be contrary to the spirit of science." Chevreul was only a young man then and a dissenter, and he was to live actively through the chemical revolution started by Woehler to reach the ripe old age of 103.

If the laws of nature were the hidden thoughts of God, then God would vouchsafe these thoughts to him if only he would work persistently enough to uncover them. Albert Einstein expressed this attitude much later in another way. "God is clever," he said, "but never deceptive." Back in Woehler's head was the suspicion that this so-called vital force was just another one of those cryptic words, a rigid line which if accepted would paralyze the progress of chemistry. Like the puzzled Chinese youngster who returned his first watch, which had suddenly stopped running, with the plaint that "it died last night," science had unfortunately endowed the chemical compounds of living matter with the hidden, sensitive springs of vitalism.

For four years after his return from Stockholm Woehler kept struggling with this problem. Then one morning he slew a dragon and the myth was gone. Before his eyes were a few long, white, needle-like crystals which the French chemist, Rouelle, magnetic teacher of Lavoisier, had first isolated from urea present in urine. Here it was, an organic chemical, and Woehler had actually made it out of lifeless compounds in a hard, inanimate flask of glass. This white compound $(NH_2)_2CO$ had never before been manufactured outside the living organism.

Woehler, who had started his career in science as a student of medicine, was terrifically excited. He was aware of the fact that he was standing on the threshold of a new era in chemistry. He was witnessing a great tragedy in science, "the slaying of a beautiful hypothesis by an ugly fact." For he had indeed synthesized or built up the first organic compound outside the living body. He saw ahead

of him a rich harvest of thousands of new products gathered from a lush new field of investigation. But he kept his head. He carefully re-examined his new product to verify its identity so there would be no question about it. When finally he was absolutely certain of his ground, he wrote excitedly to Berzelius, "I must tell you that I can prepare urea without requiring the kidney of an animal, either man or dog." Creative chemistry had arrived.

Organic chemistry ceased to be defined as the chemistry of living things. It now became known as the chemistry of the compounds of carbon since all living things contain at least one atom of carbon. The whole field of carbon compounds became the scene of feverish activity. In a century and a quarter more than half a million carbon compounds were prepared and studied. It turned out that there were more carbon compounds than compounds of any other single element.

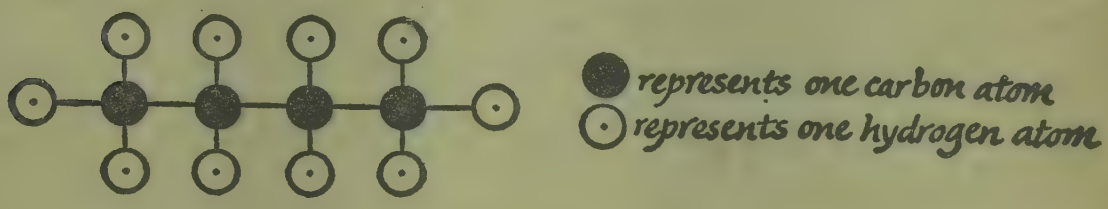
There are reasons for this. One of the reasons was discovered by Justus von Liebig, a friend of Woehler, and one of the truly great names in chemical science. As a very young man (he was three years younger than Woehler) he was working in the laboratory of the celebrated French chemist Gay-Lussac. In a Paris laboratory he was doing experiments with explosive chemicals known as fulminates. As a lad, Liebig, whose father owned a small chemical factory, had seen an itinerant tradesman making fireworks in his native city of Darmstadt. He became interested in this branch of chemistry and was doing research on some of its compounds when he accidentally prepared a very curious chemical. It was exactly the same in chemical composition as another chemical known as silver cyanate, which had been prepared by his friend Woehler.

Both of these compounds were made up of the same elements—carbon, oxygen, nitrogen and silver—and in exactly the same proportions. Yet they were entirely different in both physical properties and chemical behavior. This was indeed unique. How could two compounds composed of the identical elements, in the exact same proportions, possess different properties? The same atoms were present in the molecules of both compounds and in the same numbers. Neither Woehler nor Liebig could make

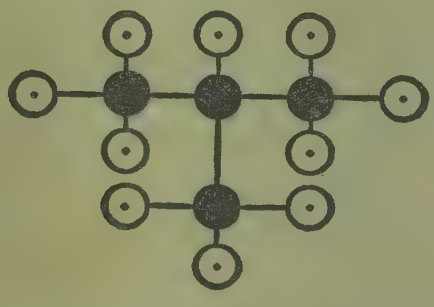
head or tail out of this puzzle, so they appealed to the great Berzelius for help. He quietly told them they had unknowingly stumbled upon a great discovery. *Isomers* was the word coined by Berzelius to designate organic compounds having the same percentage composition but different properties. Many other examples of this phenomenon soon turned up.

The explanation of isomerism lies in the different arrangement of the same atoms in different molecules. Just as a child can build different toys out of the same number and types of pieces in his Tinker-Toy set, and even as a builder can construct several different houses out of the same number and types of bricks, so the chemist can design and synthesize different molecules out of the same atoms. For example, the chemical butane, an excellent and widely used bottled gaseous fuel obtained from natural gas, is a *hydrocarbon*, a compound composed of atoms of carbon and hydrogen only. Its formula is C_4H_{10}. That is, its molecule contains 4 atoms of carbon and 10 atoms of hydrogen, and nothing else.

Returning to the little spheres of John Dalton (and chemists are doing that every day), we come up with the following picture of the arrangement of the atoms in *normal butane*:



Isobutane is an isomer, and the branched arrangement of the atoms in its molecule is:



The more atoms in a hydrocarbon, the more isomers it forms. For example, the hydrocarbon whose formula is $C_{13}H_{28}$ exists in 802 different isomeric forms!

Another reason for the enormous number of carbon compounds is found in the phenomenon of substitution. One or more of the hydrogen atoms of a hydrocarbon, for example, may be replaced or substituted for by atoms of other elements to form entirely new compounds. Thus the principal chemical found in natural gas, which may reach your home through pipes more than a thousand miles long, is a compound called methane. It is one of the simplest of hydrocarbons, and its formula is CH_4. Its graphic or structural formula is written as

Each dash in the formula is called a bond and represents a valence of one. You will note that carbon has four bonds and has a valence of four. Hydrogen, each with only one dash, has a valence of one.

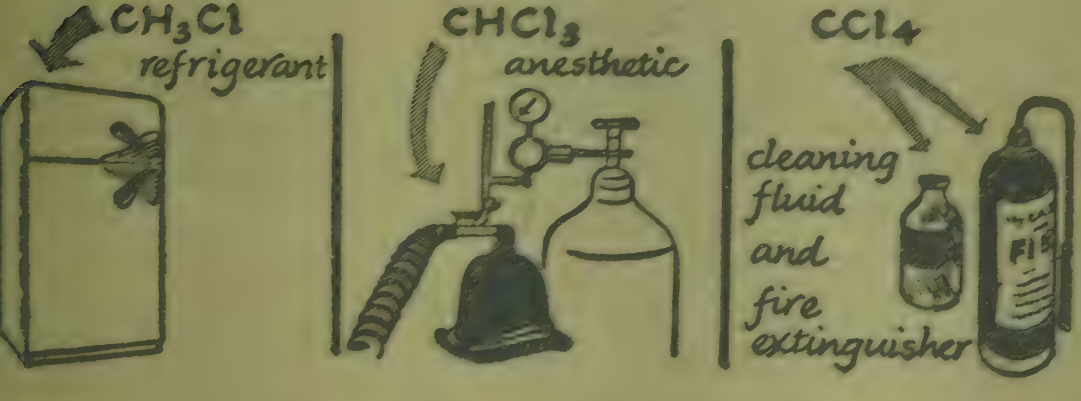
Now by means of a chemical change we can get one atom of chlorine to replace one atom of hydrogen in methane, resulting in the formation of a new compound whose structural formula is

⊖ represents one atom of chlorine

The name of this new compound is monochloromethane (*mono* means one) and its formula is CH_3Cl. It is sometimes used as a refrigerant. By altering the conditions of the chemical reaction we may substitute two, three, and even all four hydrogen atoms with chlorine atoms and obtain three more new compounds, namely:

dichloromethane (CH_2Cl_2)
trichloromethane ($CHCl_3$) and
tetrachloromethane (*tetra* means 4) CCl_4 or

At least two of these compounds are familiar to you. HCl_3 is chloroform, a colorless, sweet-smelling liquid ed as an anesthetic. CCl_4 is carbon tetrachloride, used such cleaning fluids as Carbona, in some types of fire tinguishers, and also as a fumigant. It is a colorless liq- d with a characteristic odor and is nonflammable. Such the magic of chemistry that by substituting poisonous lorine for part of an inflammable gas methane we get ther a refrigerant, a pain-relieving anesthetic, or an fective cleaning agent and fire fighter!



Other reasons for the enormous world of organic chem- try will be discussed in a later chapter. For the moment t it be remembered that Woehler and Liebig, working gether in this rich forest, expressed the thought that the hilosophy of chemistry must draw the conclusion that the nthesis or manufacture by man of any organic com- ound must be looked upon not merely as probable but as rtain of ultimate achievement. "Sugar, salicin, and mor- hine will be artificially prepared," they prophesied.

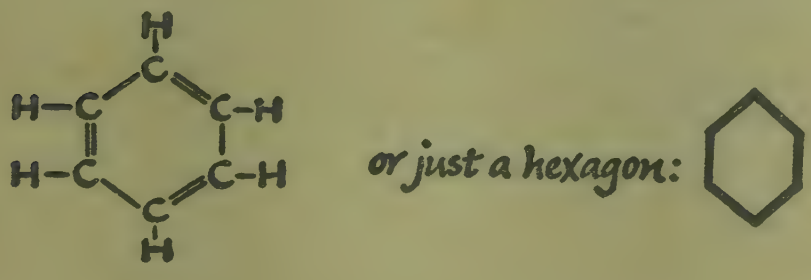
One of the really significant landmarks in the sto synthetic chemistry was the discovery of the mole structure of the compound benzene. This organic ch cal was isolated for the first time by Michael Faraday poor bookbinder's apprentice known to the worl science chiefly through his discovery of the princip electromagnetic induction. A knowledge of this prin made possible the invention and development of the namo, which ushered in the electrical age. Faraday w bit of a chemist, too. In 1825, he became interested mixture of whale oil and cod oil which a new indu just rising in London was distilling to obtain a gas u for illumination in private dwellings. He heated this li and separated out a pure colorless liquid having a dist odor. It was an inflammable fluid which was also an ex lent solvent. Chemical analysis showed its molecule to composed of 6 atoms of carbon and 6 atoms of hydro In other words, it proved to be another hydrocar (C_6H_6). Years later, this compound turned out to be en mously important, and a few drops of Faraday's first pr aration are still preserved as a historical treasure in Royal Institution in England.

The spatial arrangement of the twelve atoms in the b zene molecule was an enigma. Many attempts to pict the architecture of its molecule without doing havoc to peculiar properties were unsuccessful. Every straig chain arrangement proposed turned out to be inadequa Dozens of the top scientists of that day tried their ha at it and failed. It was very important to solve this probl because benzene was the simplest unit of one of the t great groups of organic chemicals, the aromatic grou This group was the raw material and the starting po from which (many chemists theorized) thousands of oth organic compounds could be built by substitution, ad tior and other clever ways.

The solution eluded the best minds of the day until t German chemist August Kekulé finally triumphed. H was the man who, in 1858, independently of a Scot nam Archibald Couper (who hit upon the idea at the sa time), suggested that the carbon atom, whose valence w

our, could form chains by linking. Kekulé and Couper ntroduced the graphic formulas of organic compounds. The events leading up to the discovery of the structural ormula of benzene were told by Kekelé himself and remains one of the classics of science. One day in 1865 after a strenuous stint in his laboratory Kekulé returned home very tired and fell asleep in a chair before his fireplace in Ghent. The benzene problem was still on his mind and he began to dream. In his dream he saw snakes and atoms whirling around before his eyes. The old benzene riddle was still teasing him. "All at once I saw one of the snakes seize hold of its own tail, and the form whirled mockingly before my eyes. As if in a flash of lightning I awoke and spent the rest of the night working out the consequences of the hypothesis." He had solved the knotty problem once and for all.

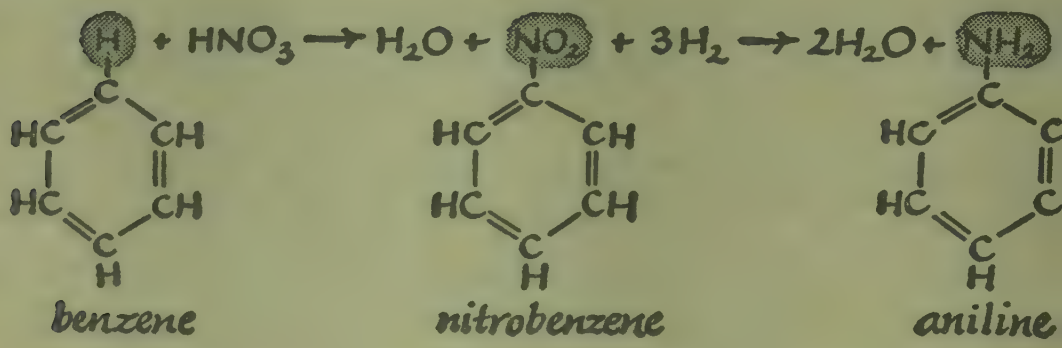
The benzene molecule was a closed-chain affair, shaped like a hexagon with alternate carbon atoms joined by double bonds. It was not an open-chain molecule like hexane or any other aliphatic compound. It belongs to the aromatic compounds named after their characteristic odor. These contain one or more units having 6 carbon atoms arranged in the form of a hexagon. Alternate single and double bonds are attached to each carbon atom. Here is the chemist's picture of the benzene molecule:



This discovery ushered in a new era in chemistry and years later, in recalling this event, Kekulé remarked, "We must learn to dream."

Benzene is the starting point in the synthesis of many so-called aniline or coal tar dyes, drugs, explosives, plastics, perfumes and flavoring extracts. Hundreds of dyes in

a wide array of colors are made today from aniline, wh
is derived from benzene by treating it first with nitric a
(HNO_3) and then with hydrogen, thus:

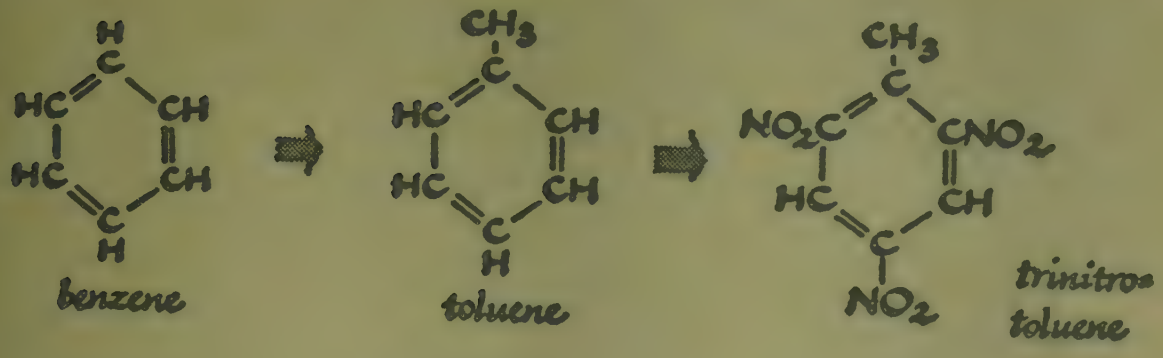


Note that one hydrogen atom of benzene has been
placed by the group or radical NO_2 from HNO_3 (nit
acid) which in turn, on the addition of hydrogen, w
replaced by another group (NH_2) to form aniline.

Again, when benzene is treated with the monochlo
methane mentioned previously, one of the hydrogen ato
of the benzene is replaced by the organic radical, CH
changing it to a new chemical known as toluene. Wh
this is then made to react with an acid (nitric) three mo
hydrogen atoms of the original benzene are replaced
three NO_2 groups to form the high explosive commo
referred to as TNT (*trinitrotoluene*). In making the va
ous substitutions or additions the chemist by controlli
various factors of the reaction must be sure to make the
at the correct places in the molecule; otherwise he will g
different compounds. For example, the positions of t
benzene hexagon have been arbitrarily marked as follow

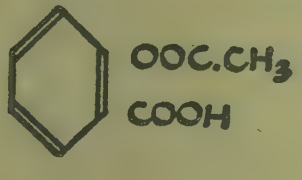
TNT is therefore designated by the chemist as 2,4,6-t
nitro-toluene.

The above changes may be represented then as follow



The synthesis of benzene derivatives in the field of medicine added many chemicals to the arsenal of the physician and surgeon. Armed with these synthetic compounds, they have fought microbes and pain and have prolonged the human lifespan. Just a glimpse of this thrilling achievement of the chemist can be recorded here.

One of the first of the synthetic chemicals created by the organic chemist was a molecule born in a German laboratory in 1899. It was made by a young research chemist, Felix Hoffman, from salicylic acid—an organic compound which had been used for centuries in an impure form as an extract from the bark of the willow, birch, olive, and poplar trees. The Greek physician, Hippocrates, "Father of Medicine," had recognized its virtues in the alleviation of pain and the reduction of fever twenty-three centuries ago. The Hottentots of Africa and the North American Indians, too, had accidentally discovered its effectiveness against rheumatism. Actually it was in chemical textbooks for more than forty years before Hoffman decided it might be used medicinally. His boss at the pharmaceutical company tried it out clinically, found it excellent, wrote a paper about it, and named it aspirin. Its chemical name is acetyl salicylic acid and its structural formula shows it to be a derivative of benzene.



Since then for more than 60 years this drug has proved the most effective, safe, and widespread single chemical for the alleviation of all pain, including pain caused by

emotional stress. And after the extravagant enthusia over the initial success of cortisone and ACTH in chro arthritis and rheumatic fever had died down, and th extended use unfortunately showed serious side effects well as rather questionable efficacy, doctors went back the old reliable aspirin tablet, reinforced in some cas with extremely dilute amounts of two drugs similar to cor sone. So broad is its use and so general is its effectivene that in the United States alone between five and ten m lion pounds of aspirin are consumed each year. In spite this, after more than half a century of medical experien we are still in the dark as to how aspirin works.

Ten years later, in another laboratory in Germany, Pa Ehrlich, M.D., son of an innkeeper, jabbed mice, rabbi and guinea pigs with injections of hundreds of newly co structed chemical compounds of his own design. He ke changing these chemicals, adding an atom here, substitu ing some group of atoms there, replacing one metal wit another element, pinpointing the changes to some specif spot in the structure of the carbon molecule, discardin chemical after chemical. He was searching for somethin special. No one had dared it before. He wanted an unusu molecule, one that would seek out and poison a specifi germ, yet be perfectly harmless to the patient. He stake his reputation and all he had on building a chemical "spe cific" against a microscopic protozoa, *Treponema pa lidum*, the agent responsible for the crippling diseas syphilis.

It was a long, rough road he had chosen. Others ha tried and given up. But not Ehrlich, that dogged, cigar addict of a microbe killer. He kept going. Then one glori ous morning, after having previously failed with 60 different experiments involving organic compounds, he di it. The 606th experiment was successful. It was an arseni compound he had drawn, 3,3′-diamino-4,4′-dihydroxy arsenobenzene (note its benzene part), that sought ou the corkscrew trypanosomes in the blood of the victi and struck down the cruel microbe of syphilis as if b magic. This new molecule had other names, salvarsan an arsphenamine, but "606" stuck as the first chemical spe cific against a murderous disease.

The discovery of salvarsan marked the birth of chemotherapy, a word coined by Ehrlich to denote the attack on the bacterial causes of sickness by means of particular chemical compounds called *specifics*. In 1908 Ehrlich was honored with the Nobel Prize, the greatest honor in the field of science. This award was founded by Alfred B. Nobel, the Swedish scientist who invented dynamite. At his death he bequeathed the sum of nine million dollars to a special body to be known as the Nobel Foundation. The interest deriving from this sum, in the form of prizes, is awarded annually to persons judged to have contributed most to the benefit of mankind in various fields including chemistry, physics, and medicine. The value of the Nobel Prize varies from year to year. In a recent year it amounted to about $45,000. Thirteen Americans have won or shared this prize in chemistry.

Even more dramatic discoveries followed this opening, events that came in the most unexpected ways. Late in December 1936 Franklin D. Roosevelt, Jr., lay in a Boston hospital gravely ill from a septic sore throat which followed a sinus infection. Streptococci had taken his body by storm and it looked as though he was facing certain death. The attending physicians had tried everything. Then someone suggested a new antibacterial chemical that had come to the United States from Germany about six months before. It was known as prontosil. It had had an unusual history.

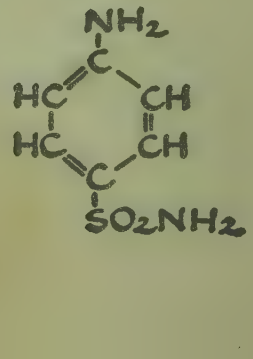
Heinrich Hoerlein, following the lead of Ehrlich, who had also successfully fought sleeping sickness with a chemical dye, had a notion that perhaps one of the many so-called azo dyes used to color textiles might be deadly to man's enemy, the streptococcus. He was director of pharmaceutical research for the powerful I. G. Farbenindustrie and had an excellent laboratory to work in, plenty of test animals and lots of money to play with. In spite of this he got nowhere, except that he came across a report in the chemical literature of a dye which seemed to show some selective action on microbes. The dye had been created by a young Austrian in partial fulfilment of the work needed to obtain his Ph.D. degree. It was a benzene derivative, a brick-red chemical that was "fast" to wool.

After Hoerlein lost interest in this dye, Gerhard Do-

magk, another German researcher with an M.D. degre picked up the trail. Like Ehrlich, he had abandoned med cine to find new bacterial killers. He refashioned the dy molecule in many different ways and tried each one c these new compounds on mice infected with streptococc One of them worked, and in 1932 he patented it as a ger micide. Three years later he tried it on a human being fo the first time. The victim was his own daughter who wa very seriously ill from blood poisoning caused by an acci dental needle prick. It worked again, and in 1935 he an nounced prontosil as an effective specific against strepto cocci infections. This was the chemical that saved the lif of President Roosevelt's son.

Other sulfa drugs soon followed, and the lives of hun dreds of thousands of other sons and daughters were saved. These drugs were ready and on hand, for example when the first bombs fell on Pearl Harbor in 1941. Pounds of sulfa drugs were dusted into the wounds of hundreds o casualties of that infamous incident. Sulfa drugs became part of the soldier's pack soon after. Special containers of sulfa tablets and powder were issued to every man going into a combat zone and he was instructed very carefully in their use.

The chemical name of prontosil, the first of the so-called sulfa drugs, is 4-sulfonamido-2′,4′-diaminoazobenzene. It was a patented product and its general use might have been restricted. Fortunately, this made no difference, for two clever French chemists had already torn its molecule apart, tested the different fragments, and finally isolated the active portion of the compound. It turned out to be para-amino-benzene sulfonamide. This had not been synthesized before, hence never patented. It was dubbed sulfanilamide, a nonproprietary name adopted by the American Medical Association. Its structural formula is much simpler. Note once more the benzene origin.



For his remarkable achievement Domagk, son of a school teacher, was named to receive the Nobel Prize in 1939. Hitler, however, had in the meantime plunged the world into war and forbade any German from accepting such an honor. But eight years later, after the death of the Nazi Führer, Domagk was presented with the Nobel Prize with due ceremony in Stockholm.

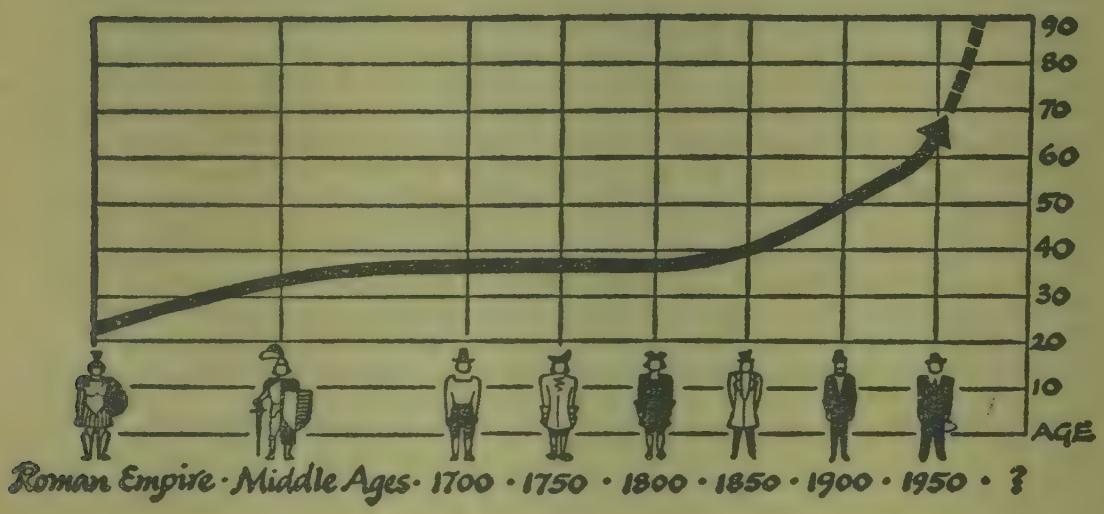
While the world was basking in the healing sunshine of the sulfa drugs, another dramatic chemotherapeutic discovery stirred mankind. It involved not one but a whole group of chemicals, a veritable phalanx of molecular soldiers jumping to arms from molds in the soil, mighty warriors equipped with new and terrible weapons to wage successful war against some of the oldest and deadliest killers of men. Antibiotics, they came to be called (from *anti*, against, and *biotic*, relating to life). Antibiotics went after germs in the body, strangled them to death or slowly and subtly starved them of some indispensable food such as PABA or paraminobenzoic acid.

The sulfa drugs combat the streptococci not by killing them at once but by checking their multiplication, leaving the natural leucocytes of the blood to pick off the invaders. The new and more versatile chemical molecules strike directly, and are equally deadly to the staphylococci responsible for boils, abscesses, and other pus-forming infections as well as against tuberculosis, meningitis, influenza, and pneumococcal pneumonia.

So effective were these antibiotics, sometimes used in conjunction with the sulfa drugs, that in the short span of a few years the death rate from influenza and pneumonia dropped more than 50%, and that from mastoid and other diseases of the ear more than 90%. Physicians, busy for years tending to the sinus, ear, nose and throat ailments of long lines of patients, were soon compelled to switch to other branches of medicine. Mastoid surgery in cases of the middle ear infections was practically abandoned. The death rate from meningococcal meningitis dropped 95%. The gonococcus invader was destroyed in most instances by a single dose of one of these antibiotics—penicillin—and daily intakes of the same chemical over a period of about two weeks almost wiped out primary syphilis in this

country. Peritonitis was no longer the dread of surgeons, and mothers no longer feared childbed fever.

Mainly because of this new chapter in chemotherapy, life expectancy in the United States climbed phenomenally from 62.9 in 1940 to 68.5 in 1951 and to 70.3 in 1960. (The figure was about 44 in this country in 1889.) In Southeast Asia and parts of South America the average lifespan is still only about 30 years—one child in three dies before the age of one.



First of the antibiotics to be introduced was penicillin, in 1942, followed by streptomycin in 1944, bacitracin the next year, dihydrostreptomycin in 1946, chloromycetin the following year, aureomycin in 1948, neomycin in 1949, terramycin in 1950, erythromycin in 1952, tetracycline in 1953, kanamycin and novobiocin in 1957, and colistin in 1960.

Among the scores of men who toiled to give us the miracle drugs, two names stand out above all the rest: Alexander Fleming, who left a farm in Scotland to study in St. Mary's Hospital in London, and Selman A. Waksman, who came here in 1910 as a young man of 22 from Kiev in the Russian Ukraine to achieve fame at Rutgers University in New Brunswick, New Jersey. Both were honored with the Nobel Prize. Fame sneaked up on the farmer boy while he was repeating a routine he had followed for years. He was playing nurse to a rather virulent strain of staphylococci gamboling in some fresh broth in

some run-of-the-mill Petris or flat covered glass dishes. He had left one of them resting comfortably on the window ledge of his laboratory. Below his window was dusty old Paddington Railway Station from which he had departed in September, 1928, for a short vacation in the country. Upon his return he started, almost mechanically, a routine examination of the culture growths in the various dishes.

One observation that morning was unique. He noticed a patch of blue-green mold about the size of a quarter around which was a clear area that separated it from the staphylococci culture. Here the staphylococci colony seemed to have melted away. It had been engulfed and destroyed. "I had not the slightest suspicion," wrote Fleming, "that I was at the beginning of something extraordinary, but I wanted to pursue the subject." He found that the broth surrounding the mold was nonpoisonous to laboratory animals. However, he delayed following up his discovery because, as he explained later, "I am a bacteriologist, not a chemist, and I was working in a bacteriological laboratory in which there was no skilled chemist." Here is an excellent argument, by the way, for group research.

Then came World War II. Men were dying in large numbers from wounds and infections picked up on the battlefield. Men, women, and children, too, were dying during the blitz in England. More effective bacterial killers were urgently needed to reduce the high mortality. Destiny stepped in. Two men teamed up. One was Howard Walter Florey who had come to Oxford, England, from Australia with a Rhodes scholarship. The other was Ernst Boris Chain, German-Jewish refugee from Nazi persecution. Together they decided in 1938 to make a thorough investigation of the literature of antibacterial research in the hope that this might furnish a clue for further work. Sure enough they soon came across Fleming's paper and rediscovered the mold spore of *Penicillium notatum* which had shown evidence of toxicity towards germs in a group of mice they had used as test animals.

A vigorous program of research was started to isolate the active chemical portion of the mold product. When grown on a special broth or culture medium this green

mold secreted an antibacterial substance called penicillin from the Latin *penicillus* which means a small brush or tail, as the tips of the fibers were tufted this way. Early in 1941 they had accumulated a spoonful of impure penicillin. A London bobby was dying of blood poisoning. He was given a shot of the stuff and he began to respond beautifully. More penicillin was needed but the victim died before they could extract it. There was no doubt that penicillin could save lives. The work was speeded up, more funds were made available, more assistants were hired. Fleming, too, was in the thick of the work. Eighteen months later Florey handed Fleming some of the pure yellow powder which Chain, the chemist, had crystallized out of the broth. With it Fleming saved the life of a friend who was dying of meningitis.

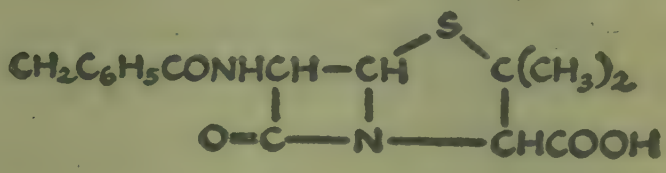
The lifesaving drug was here. There was no longer any doubt about it. It became imperative now to make it on a large scale. Quick, careful, mass production methods could do it. England was being blitzed and could not undertake to do this. Florey and another doctor rushed to the United States for help. Three members of the American pharmaceutical industry—Pfizer, Merck, and Squibb—joined together to do a huge job of biochemical engineering. They were aided by a government grant of $20 million to help expand their existing facilities, and to build new plants for the manufacture of large quantities of pure penicillin. The mold produces several closely related substances whose formulas differ only slightly. Commerical preparations contain mainly penicillin G.

Within two years, the mass production problem was cracked, and penicillin from molds was being turned out in almost unlimited quantities. In 1944 one billion units of penicillin cost $200 wholesale. The following year this figure dropped to $7, then to $1, and finally to just a few cents. In the first ten years of its manufacture, 3000 tons of penicillin were made. Penicillin and its derivatives poured out of drugstores and became available to all.

Fleming refused all profit from his discovery and turned over his financial rights to the institute of which he was the director. Fleming was knighted, Florey became Sir Howard, and Ernst Boris Chain, by this time an English sub-

ject, shared the Nobel Prize with Fleming and Florey in 1945.

In the meantime chemists had gone to work to find out the chemical construction of the penicillin molecule. This was determined by Dorothy Crowfoot Hodgkin, a Fellow of the Royal Society of England, and the mother of a young family. In 1957, after nine years of laborious and painstaking work, Professor John C. Sheehan of the Massachusetts Institute of Technology and his associate Dr. K. R. Henery-Logan finally synthesized penicillin V. The structural formula of penicillin G, $C_{16}H_{18}O_4N_2S$, is



In the meantime, Waksman, the young Russian immigrant who had spent a quarter of a century working with microbes present in soil, had suddenly made a very lucky switch. He had already gained quite a reputation as an authority in microbiology, the study of soil bacteria in relation to agriculture and industry. Now he turned his experience and talents to the search of soil microbes that could be used in the struggle against the diseases of man and beast. He was led to this decision partly by the success of one of his former students, a young Frenchman named René Jules Dubos, who had isolated the first antibiotic in pure form. It was named *gramicidin*, and though not effective against human ailments it did save his laboratory mice from many bacterial attacks. Furthermore, there was a war of survival being fought, and Waksman, like Florey and Chain, saw the urgent need for new chemical agents to save soldiers and civilians against the rising curve of infections that have always accompanied wars.

Waksman worked feverishly for several years but made no headlines. Then late in 1943 he electrified the world with the discovery of a new antibiotic which he named *streptomycin*, from the Greek *streptos*, curved, and *mykes*, fungus. He had found it in a sample of soil from New York which harbored a mold, a species of actinomycete

first isolated by him as far back as 1915 in his early research days. Streptomycin did a spectacular job against kidney infections, inflamed gall bladders, and several other diseases of man. When combined with another new chemical isoniazid derived from nicotinic acid it is effective in the treatment and prevention of tuberculosis. Almost overnight it became a household word. By 1946 people shared a mere 3,000 pounds of it. Ten years later they were gorging themselves on 450,000 pounds of streptomycin and its cousin, dihydrostreptomycin. From a cost of $25 a gram, it was tagged down to 75¢ just as a new Institute of Microbiology at Rutgers University was dedicated in honor of Waksman. This had been built with a nest egg of $3,500,000 accumulated from royalties from the sale of his streptomycin.

Others, too, started a mad scramble to unearth new and perhaps even more potent mold drugs. A retired botany professor of the University of Wisconsin came up with golden yellow aureomycin from the soil of Missouri, and a Yale professor isolated chloromycetin from a soil mold brought from Caracas, Venezuela. Kanamycin was unearthed from a Japanese flower bed on the grounds of Nagoya University. The large drug and pharmaceutical houses joined the party. They remembered the bonanza they had struck less than twenty years before when creative chemists presented them with a string of vitamins whose retail sales climbed to almost one hundred million dollars in 1954.

These pharmaceutical firms were at the moment in the midst of a bull market in sulfa drugs and penicillin, the sales of which by the 1950's were to amount to more than $100 million each. Even aspirin and aspirin mixtures were being swallowed to the tune of approximately $200 million a year. By 1960, $340 million was spent in this country for antibiotics and an equal fortune for tranquilizers. The United States Pharmacopeia contained more than 100 new antibiotics and other drugs, and 90% of all the drugs and pharmaceuticals sold by the corner drugstone in that year were to be for medicines which had not even existed in 1950. During these ten years there was a twenty-fold

increase in major discoveries in drug research in this country.

There was gold in these antibiotics, and drug manufacturers plunged into the business of finding more of them. Hundreds of thousands of soil samples came pouring into their expanded research laboratories. In this world-wide hunt for new chemical specifics, hundreds of bacteriologists and chemists went through the business of screening, washing, cooking, treating, culturing, and crystallizing the active components of their molds. One firm literally screened a million dirt piles in this pot-of-gold venture. One antibiotic turned up from the soil of the Philippines and was named filipin, another from the soil of Ramna in faraway Pakistan was dubbed ramnacin. Still another from Hawaii was called bryamycin. Finding pleasing and appropriate names for these new products became a sizable chore. Even the big brain of an IBM machine was commissioned to help.

In this stupendous undertaking a few powerful so-called broad-spectrum antibiotics were introduced. These are drugs which treat not only one or two single diseases effectively, but are potent with a whole range of infections. The most useful of these is tetracycline which successfully fights such diseases as trachoma, psittacosis, and the rickettsias. The job of synthesizing all of these chemicals is well under way. Chloromycetin was the first to surrender. It is no longer made from a mold.

Elated with the countless number of successes in the field of medicine, chemists tackled the problem of synthesizing important drugs hitherto obtainable only from a plant, animal or other natural source. The synthetic chemist had already given the physician all of his anesthetics—man-made ether, chloroform, nitrous oxide (laughing gas), ethyl chloride, ethylene, cyclopropane, and nonflammable trichloroethylene. Nitroglycerine, which dilates the coronary arteries and relieves the pain of angina pectoris, synthetic procaine or novocaine, pentothal, the barbiturates, ephedrine, veronal, dramamine, dromaran, and benzedrine are just a few more man-made drugs that were delivered to the medical man by the synthetic chemist.

But what about the vegetable drugs such as quinine,

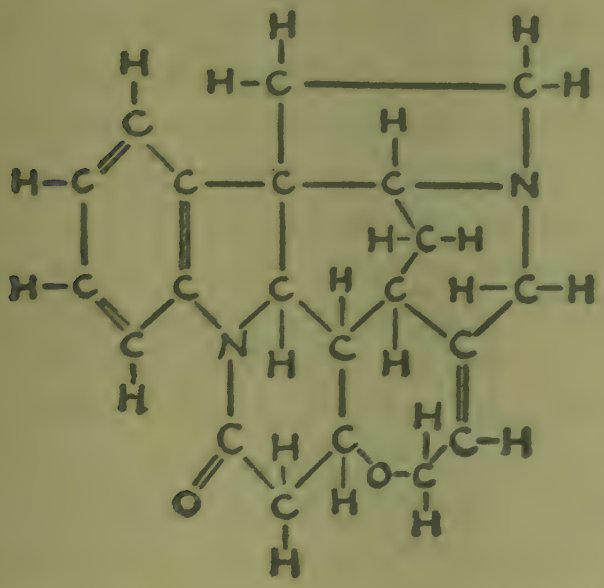
morphine, and strychnine? Quinine had for years been the only specific against malaria, a scourge that laid low millions of people each year and cut short the lives of other millions. Malaria, the world's number one disease problem, is caused by an unusually obstinate parasite that is introduced into the blood stream of its victim by a mosquito. Men had learned by accident many years ago that quinine, a drug extracted from the bark of the cinchona tree, could hold this disease in check.

Since most of the world's quinine production was concentrated in the Netherlands Indies it was imperative to find a way of making it synthetically. During World War II this area, now known as the Republic of Indonesia, fell into the hands of our enemies and chemists began a more intensive hunt for a quinine substitute or man-made quinine. Two synthetic chemicals, atabrine and plasmochin, resulted. Synthetic chloroquine was another antimalarial. But they were not true quinine. Creative chemistry was faced with a real challenge again. The determination of the architecture of the complicated quinine molecule and the more difficult synthesis of this chemical eluded chemists of many countries for many, many years. It was a tantalizing target.

New techniques, new instruments, new data were all brought into play. First, a blueprint of the molecule was drawn. It turned out to be a formidable molecule whose formula is $C_{20}H_{24}N_2O_2$. To put this molecule together from small bits of raw chemicals was indeed a prodigious undertaking. Atom by atom and radical by radical two 27-year-old chemists from Harvard University assembled the many intermediate products until these were all joined to form the identical quinine molecule that nature had prepared for man in the cinchona tree. In 1944 Robert B. Woodward, who at the age of 20 had received his Ph.D. from the Massachusetts Institute of Technology, and his co-worker, William Doering, announced the news that the United States could be freed from foreign sources of this vital drug. Eight years later, morphine, $C_{17}H_{19}O_3N$, was also synthesized.

What about strychnine, so essential in small doses as a stimulant to the nervous system? That, too, was finally

conquered. It was 1954 when the same Woodward, with the help of several associates, finally synthesized it by a process involving as many as thirty separate, intricate steps. This came after more than a century of labor by countless men and women. The formula of this compound is $C_{21}H_{22}N_2O_2$ and its graphic structure may be represented by the following:



strychnine

Then two new drugs flashed on the medical horizon early in 1949, promising quick relief from the crippling effects and excruciating pains of rheumatoid arthritis and rheumatic fever, the most common causes of chronic ailments. Cortisone and ACTH (the *a*dreno-*c*ortico-*t*ropic *h*ormone) were the new challenges. The first was extracted from the cortex (bark) of the adrenal glands (located above the kidneys) of cattle, and the second could be obtained from the pituitary glands (located at the base of the brain) of hogs. Chemistry and medicine, by joining hands in the study of the vitamins, had won a great victory over death in the first three decades of the present century. So chemists and doctors again did not fear to enter together upon investigations of other products of the human body. Among these products are the substances manufactured by the glands of internal secretion. These glands manufacture complex chemical substances which are emptied directly into the blood stream rather than through ducts into specific regions of the body. Such substances are called hormones from the Greek meaning *I excite,* and

enter into the chemical control of various body processe

John J. Abel of Johns Hopkins University was the fi to isolate a hormone derivative in pure or nearly pure for He obtained the hormone epinephrin in 1897 from t adrenal glands of sheep. Jokichi Takamine, a Japane chemist in Clifton, New Jersey, soon after obtained pu crystals of the same hormone which he marketed under t name of *adrenalin.* Five years later it was synthesize Adrenalin proved of inestimable value to physicians. As stimulant and as an astringent it is used both in treatin heart ailments and in stopping the bleeding of wounds. I the body, adrenalin is necessary whenever unusual phys sical exertion seems likely. For example, in fright or ange adrenalin, in very minute quantities, is secreted into th blood stream. As a result, the liver is stimulated to activity and increased amounts of sugar are poured into the blood Adrenalin also causes the walls of the arteries leading t the large muscles to relax, thus enabling this larger tha normal amount of energy-producing sugar to reach th points at which it is needed. Adrenalin also causes th heart to beat faster and harder and, in apparent anticipa tion of injury, increases the clotting ability of blood.

Thyroxin, the hormone secreted by the thyroid gland which lies like a saddle over the larynx, is another most important compound. It is directly related to goiter and to the general metabolism of the body. Estradiol, a hormone of the female sex gland and testosterone, a male hormone, appear to be responsible among other things for the development of sex characteristics and certain changes in the reproductive cycle. Estrone, oxytocin, vasopressin, and insulin also belong to this family of chemicals.

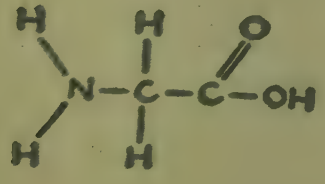
With very impure extracts of cortisone and ACTH, Dr. Philip S. Hench, one of the leading authorities on arthritis, and Edward C. Kendall, the biochemist who first isolated cortisone, both of the Mayo Clinic, in Rochester, Minnesota, demonstrated that they could control rheumatoid arthritis and rheumatic fever in many cases. Cortisone works directly whereas ACTH has the effect of stimulating the adrenal glands to produce more cortisone in the body. This was an electrifying announcement. Five million disabled people cried out for deliverance in the

United States alone. But both of these extracts were extremely scarce. They were difficult to obtain in sizable quantities since they were present in the glands of animals in extremely minute amounts. To obtain a single gram—less than $\frac{1}{30}$ of an ounce—180,000 sheep had to be slaughtered. The pituitaries of tens of thousands of hogs had to be scraped and treated before an equal weight of ACTH could be gathered together. Besides, even with the most careful separations these hormones were often mixed with some impurities.

With a feeling of great urgency, chemists again went to work to prepare the pure compounds. These, at last, might be the molecules that could lock horns with the dragons of rheumatoid arthritis and other illnesses and slay them on the spot. Many joined the adventure. Woodward again won the battle, at least with cortisone ($C_{21}H_{28}O_5$). He not only determined its molecular structure but finally also synthesized it in 1953.

But ACTH was infinitely more stubborn. It refused to yield even to the most skillful of synthetic chemists. There was good reason for this impasse. ACTH belongs to a group of organic compounds called proteins which are the most complex of all chemicals. The word protein was first suggested by Berzelius and is derived from the Greek, *proteios*, of the first rank. They are distinguished from carbohydrates and fats by the presence of nitrogen which is present in their molecules to the extent of about 16%. In addition, proteins contain carbon, oxygen, hydrogen, and sometimes small amounts of sulfur and phosphorus.

Proteins can be broken down into simpler units called amino acids by boiling them several hours with acids. Even the amino acid fragments are by no means simple compounds. There are 25 of them that have already been identified. They have also been synthesized. The simplest is glycine, whose structural formula is



Some idea of the complexity of the proteins may be gaine from the fact that more than 1,000 atoms may be preser in a single molecule of a protein. Molecular weights c typical proteins vary from about 17,500 for lactalbumir a protein found in milk, to about 6,700,000 for hemocy anin, a protein found in blood, and even higher. Som other pure proteins are egg albumin (the white of eggs) casein of milk, gelatin of bones, and keratin of hair. Ther is no known life without proteins for they are the essentia components of enzymes, hormones, genes and protoplasn —that colorless, jellylike substance that makes up all living cells. Even the most complicated molecules whose structures have already been shown are simple in comparison to the simplest of the proteins.

In spite of this, scientists in several laboratories attempted to determine first the molecular structure of ACTH. Finally in 1955 two teams of research scientists working in the laboratories of the American Cyanamid Company and another team operating at the University of California came up with its three-dimensional picture. They reported that it consisted of no less than 59 amino acid units linked together in the form of a long chain of atoms. In the face of this frightening complexity, the almost impossible task of putting its pieces together by synthesizing pure ACTH out of simpler raw materials was begun. In 1960 Klaus Hofmann of the University of Pittsburgh synthesized a chemical biologically equal to ACTH. It contains 23 different amino acids instead of the 59 of natural ACTH.

ACTH was not the first protein whose chemical architecture was unravelled. This honor belongs to the hormone insulin secreted by the pancreas gland. The absence of this hormone produces diabetes. It is one of the smallest of the proteins. It is constructed of 51 amino acid units including 17 different ones. Its formula is $C_{254}H_{377}N_{65}O_{75}S_6$. It contains in all 777 atoms to the molecule and its molecular weight is 5727. In 1954 Frederick Sanger and his associates at Cambridge University in England, after ten years of exhaustive work, took some pure crystals of insulin which in turn had taken years of blood and sweat by other scientists to prepare, broke them down piece by

piece and bit by bit until they had worked out the complete structure of its molecule. Its full structural formula would fill two whole pages of this book. He was awarded the Nobel prize four years later.

Chemists are not ready to lay down their beakers and stirring rods, for insulin is still a reluctant deliverer. It has to be injected under the skin of a diabetic to be effective. Unstable towards many body fluids, it cannot be taken orally, as the ferments of the digestive tract split it into pieces and render it innocuous. Chemists want to save the two million diabetics in this country from the dreaded prick of the needle. Perhaps the whole of the insulin molecule is not needed for its lifesaving effects. Perhaps one potent portion that is resistant to the juices of the alimentary canal will some day be found.

In the meantime they have very lately synthesized several substitute organic compounds which when taken orally lower the high blood sugar of mild cases of diabetes. Among them are two sulfonylureas, and a guanidine (phenformin).

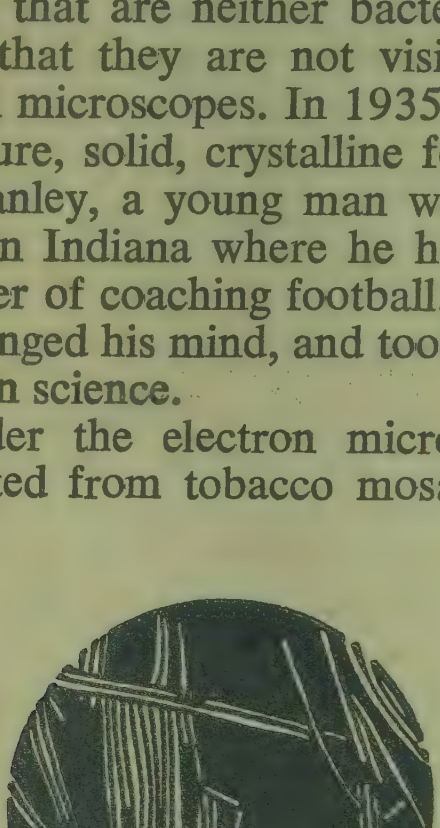
Having taken these two chemical watches apart and painstakingly studied all of their many and intricate parts, the chemist was confronted with an even more difficult task—that of putting them together and synthesizing the first protein molecule in history. Could they really manufacture a protein that would tick as effectively as the natural insulin of the animal body? Thus far, no success. Proteins still defy synthesis. However, the world awaits such a chemical miracle with hope and a modest degree of assurance that it will be accomplished soon.

In the meantime, biochemists have laid siege to the citadels of two other classes of protein compounds, enzymes and viruses. Hundreds of enzymes in the body make possible the myriad of chemical changes without which life would be snuffed out. Pepsin in the gastric juice is such an enzyme. Enzymes work in extremely minute amounts. One molecule of an enzyme will activate millions of molecules of other compounds and do it at body temperatures rather than at much higher heats required without them. One ounce of the enzyme rennin in rennet powder obtained from a calf's stomach will clot

3,000,000 quarts of milk. The first of these proteins to b isolated in pure crystalline form was urease. The feat wa accomplished in 1926 by James B. Sumner of Corne University. He extracted it from the jack bean, and turned out to have a molecular weight of nearly half million. Since that historic day, about half a hundre other enzymes have been captured by scientists in pur form.

The other protein compound being researched—and another possible precursor of life—has also partially ca pitulated to the chemist. Viruses are disease-producing agents that are neither bacteria nor protozoa and are so small that they are not visible under the highest-power optical microscopes. In 1935 the first virus to be obtained in a pure, solid, crystalline form was isolated by Wendell M. Stanley, a young man who had come out of a small town in Indiana where he had first hoped to embark on a career of coaching football. At the University of Illinois he changed his mind, and took the road that led to a Nobel Prize in science.

Under the electron microscope a virus Stanley had extracted from tobacco mosaic (a disease which attacks



Electron micrograph of tobacco mosaic virus (magnified 50,000 diameters)

the tobacco plant) turned out to have a strange, rodlike form, and an estimated molecular weight of many millions. Many other viruses have been identified and isolated. Viruses seem to lie between the worlds of the living and the dead. "They serve as a bridge," said Stanley, "between the molecules of the chemist and the organisms of the

bacteriologist." Outside the living cell of a tobacco plant, the virus of tobacco mosaic acts like any other complex molecule. However, inside the living cell, it is capable of reproducing itself—a characteristic of living things.

Many human diseases such as influenza, the common cold, virus pneumonia, smallpox, polio, mumps, psittacosis, and measles are caused by viruses. The human influenza virus was discovered in 1933. Fifteen years before, this virus had caused an influenza pandemic which attacked 500 million people around the world and killed 15 million of them. In the United States alone half a million people died of influenza in four months. The isolation of this and other deadly viruses, the determination of their structural formulas, and finally their syntheses would help in the battle to wipe out some of the most insidious enemies of man, by giving us the causative agents of certain diseases on which we could conduct experiments directly.

The chemist is working on this stupendous problem. Some progress has already been reported. In the summer of 1955 two teams of scientists, one at Washington University in St. Louis and the other at the University of California Virus Laboratory headed by Stanley, succeeded in tearing the tobacco mosaic molecule apart. Each part was found to have lost the original activity of the parent virus. Then they put the "dead" parts together and restored the infective activity of tobacco mosaic completely. Furthermore, Stanley's associates reported the same year that they had obtained pure crystals of the first animal virus—the one that causes polio.

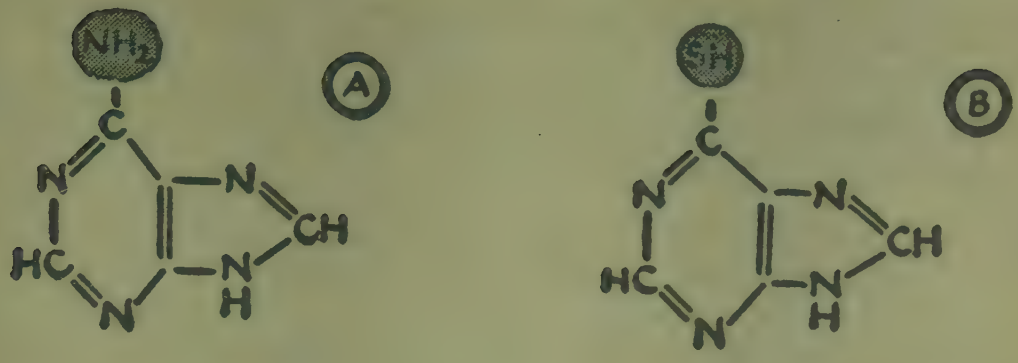
Linus Pauling, Nobel Prize winner of the California Institute of Technology, world-famous authority on the structure of proteins, and no ivory-towered chemist in this field, has made a daring suggestion: after we have succeeded in determining the structure of a protein molecule, we can then make a straightforward attack upon specific diseases by plotting the molecular structure of a desired drug, in such a way that it would interact with some abnormal molecule that causes some disease. We could thus directly control or even destroy many diseases such as sickle cell anemia which is the result of abnormal

hemoglobin molecules in the blood. According to Paulin "molecular medicine" is the medicine of the future. Th chemist no longer fears to approach compounds that lie o the very rim of life itself.

Synthetic chemists have not neglected the dark maze of the mental diseases nor the wild growth of cancer cells each of which continues to take its frightful tolls. Th attack on the first has been long and heartbreaking. Reser pine, chloropromazine and meprobamate are three o the synthetic drugs that have come out of the chemist's crucible to try to bring peace of mind and serenity to mil lions of mental patients. These tranquilizers have helped to cut away restraints and to change the mental hospital atmosphere. In 1956 reserpine was synthesized by—again —Harvard's Woodward and his associates. Chemists at the Squibb Institute of Medical Research achieved the same result independently and at the same time. We are no longer dependent upon the foreign snakeroot plant from which it was formerly extracted.

For several decades, too, the chemical attack on cancer has intensified. This avenue of approach has been explored in the belief that perhaps some chemical compound can be found that will either inhibit the growth of the cancer cell or destroy it completely without harming the normal body cells. Some 20,000 synthetic organic chemicals and many thousands of other chemical mixtures have been tested within the last few years. As yet there have been some isolated successes but no major breakthrough. The ingenuity of the chemist has been pitted against one of the most subtle of human destroyers.

One of the many lines of attack employed is to seek out some chemical essential to the life of the cancer cell and then to feed it with some other chemical contrived to resemble this life essential very closely yet be deadly to it. For example, the chemical *A* shown here on the left is needed for the growth of the cancer cell. The chemical *B* shown on the right inhibits the growth of the cancer cell. The cancer cell, mistaking the second molecule for the first, will be fooled and ingest it, and, it is hoped, will be conquered.



It is hardly necessary to keep piling Pelion upon Ossa. You are probably aware by this time that the synthetic chemist of today is endowed with incredible perseverance and fabulous ingenuity. Almost a century ago the *Journal of the Goncourt Brothers* contained an entry by these two famous French novelists and historians of a conversation between two scientists who were discussing the possibility of the organic chemist finally creating life synthetically in competition with God. They wound up their discussion with the observation, "We have the feeling that when this time comes to science, God with His white beard will come down to earth swinging a bunch of keys, and will say to humanity the way they say at 5 o'clock at the saloon: 'Closing time, gentlemen.' "

The American philosopher Ralph Waldo Emerson took another view of such a possible occurrence. For him scientific triumph was not the death, but the birth of further mysteries and greater goals. "I do not know," he wrote, "that I should feel threatened or insulted if a chemist should take this protoplasm or mix hydrogen, oxygen and carbon [he might have added nitrogen had he known that proteins also contain this element], and make an animalcule incontestably swimming and jumping before my eyes. I should only feel that it indicated that the day had arrived when the human race might be trusted with a new degree of power and its immense responsibility; for these steps are not solitary or local, but only a hint of the advanced frontier suggested by an advancing race behind it."

5 More and Better Food for Millions

THE chemist has not only saved millions from premature and sudden death, but he has also helped to maintain good health for more millions by providing mankind with better food and a greater abundance of it. The chemist learned how to satisfy the peculiar tastes of the soil and how to cater to the needs of the soil's myriads of tiny inhabitants. And through it all he had to wage a stubborn and continuous war against the enemies of plant life—and the hosts of parasitic fungi, the bug world, whose little creatures, too, had to eat to keep alive. Either man got the food or the beetles or fungi beat him to it. There just was not enough for both.

Throughout the world this is still a crucial struggle. During the last three decades, world food production has increased only 10%, whereas the population growth was 30%. The average man's daily need runs to about 2800 calories. Scarcely one third of the world's people can scrape this much together. We in the United States are, of course, much better off. In this same period of time while our population increased 30% our food production jumped 50%, thanks in part to the work of our chemists. In fact, we are now producing more than we can eat. Farm surpluses keep mounting in our country and the government is trying to evolve a program of reducing production. It is a paradoxical picture. Obesity, caused by overeating, is one of the major medical problems of the United States—while undernourishment and malnutrition are the primary problems of enormous areas of the rest of the world. One third of the world goes to bed every night hungry!

To improve the food situation of the whole world and keep at least one step ahead of the billions of Beelzebub's realm, chemists with all their knowledge and creative impulse keep working to increase man's food supply, for many problems still remain unsolved. To understand this struggle more clearly, let us go back to some of the chemi-

cal elements again. Of the 103 known elements, 83 are metals. These elements are usually hard, lustrous bodies that have great tensile strength, can be hammered into sheets, drawn into thin wires, and conduct heat and electricity very well. About 15 of the remaining elements are the nonmetals. They are usually brittle solids or gaseous bodies.

The metals are the more familiar elements. They are used as pure elements or alloys (mixtures)—steel to build machines, copper to carry electrical messages, gold to adorn and to serve as a medium of exchange, chromium to decorate an automobile or glamorize a kitchen. Not so with the nonmetals. Possibly you may have seen and handled pure sulfur, but it is doubtful if you have ever seen, no less handled, pure phosphorus. You may have been annoyed by the sharp odor of chlorine, but you surely have not come face to face with free bromine. As for iodine, you know it only as tincture of iodine, the antiseptic consisting of solid iodine dissolved in grain alcohol. Invisible oxygen and nitrogen are, of course, also nonmetals.

In general, the nonmetals, unlike the metals, find their widest use in compounds rather than in the free state. Thus sulfur is one of the raw materials used in the manufacture of sulfuric acid—most widely used acid of industry—as well as in the making of pulp, paper, and matches. Phosphorus, too, falls into this classification. This element was discovered in 1669 by an alchemist, Hennig Brand. He lived in Hamburg, Germany, where, still in search of the grand elixir of life, he experimented with everything he could lay his hands on. Nothing was too repulsive for his flasks or his crucibles. Out of human urine he finally isolated, after innumerable operations, a white, waxy solid that shone in the dark and caught fire in the air spontaneously, burning with a thick white cloud, which could dissolve in water. So unusual was this substance that Brand made a triumphant and lucrative tour of Europe exhibiting its strange properties to gaping thousands.

Because of its extreme chemical activity it is naturally never found in the free state as are gold, copper, and silver. Phosphorus occurs most abundantly in a chemical

compound called calcium phosphate, $Ca_3(PO_4)_2$. This i the stuff of which our bones are made. It is the whit skeleton left after the liquid and fleshy parts of a dea animal decompose and gradually disappear as vapors an gases. The skulls and bones of animals that have perished in the desert are familiar sights, especially to Western movie fans. In Florida and several other states there are wide and deep deposits of the phosphate accumulations of the bones of countless animals that roamed these areas thousands of years ago. Because of the warm, dry climate and the thick layers of sand and earth that gradually covered them, this chemical phosphate resisted weathering and chemical change and remained unaltered in chemical composition.

Calcium phosphate is insoluble in water but when crushed into a fine powder and strewn over the ground it is very slowly acted upon by mild acids present in the soil. As a result of this action, calcium phosphate is converted into a soluble salt which provides phosphorus to plants. Much quicker action is obtained by treating the rock phosphate with sulfuric or nitric acids, which convert it immediately into a soluble superphosphate fertilizer, containing about 17% of phosphorus oxide. Triple superphosphate is a more concentrated phosphate fertilizer developed by the Tennessee Valley Authority, a government agency created by the Congress back in 1933. Since most soils in the Tennessee Valley are deficient in phosphorus, a plan was formulated for phosphate manufacture using the raw phosphate rock of Tennessee. Triple superphosphate is now widely used throughout the nation. It contains about three times as much available phosphorus as ordinary superphosphate. It is made by the action of phosphoric acid on calcium phosphate. Calcium phosphate is the calcium salt of phosphoric acid.

Today these phosphates represent our richest sources of phosphorus fertilizers. A fertilizer is essentially a plant food. When properly selected and applied, it represents the milk, the egg, the vitamins, the leafy vegetables, and all the protective foods combined to give a growing child a balanced diet. Crops require many elements for normal growth and development just as we ourselves would ail

or even die before our time if we did not obtain from the food we eat an adequate supply of at least 26 chemical elements including iron, calcium, iodine, phosphorus, sodium, potassium, chlorine, fluorine, lithium, cobalt, molybdenum, sulfur, magnesium, silicon, manganese, copper, selenium, boron and zinc—and, of course, carbon, oxygen, hydrogen and nitrogen.

For example, it took many years of careful research to discover that a small amount of the element iodine is essential to normal life. This element finds its way into the molecule of a hormone called thyroxin, manufactured in the thyroid gland located around the larynx and windpipe. Hardly a pinch of this crystal is present in the human body at any one time, and yet it stands between normal mentality and idiocy, and even between life and death. When the thyroid gland receives too little iodine, goiter —an enlargement of the thyroid—results, caused apparently by the attempt of the gland to increase its size in order to produce more thyroxin. To offset this deficiency, an iodine compound may be added to drinking water, or about 0.02 per cent of sodium iodide to so-called iodized salt.

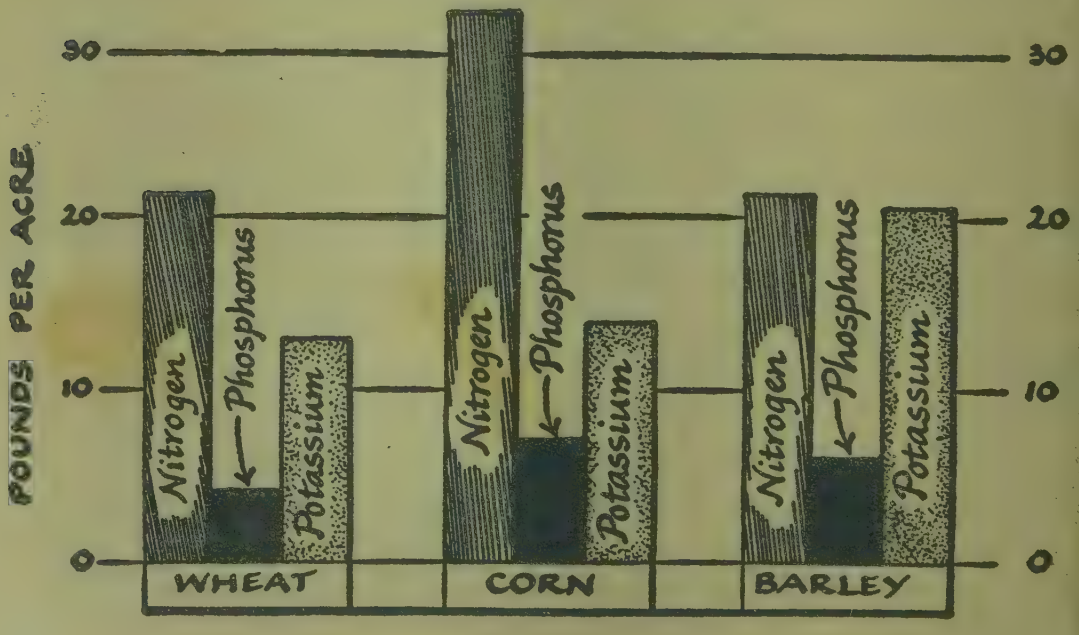
Extreme underactivity of the thyroid gland in newborn babies and young children may result in cretinism—misshapen dwarfishness, low mentality, sluggishness, dullness, slow heart action. Cretins were once doomed to an early death. They seldom lived beyond the age of ten. Thyroxin, now made available by the synthetic chemist in unlimited amounts, is used in the treatment of this thyroid disorder. It puts the cretin on the road to normality. Overactivity of the gland in supplying too much iodine often produces the opposite effect—the thin, nervous, highly energetic person whose movements are quick and whose heart action is rapid. Iodine in correct amounts is also necessary to other forms of animal life. Large quantities of iodides are added to commercial feeds for chickens, cattle, dogs, cats, and other animals, and to fertilizers for forage crops.

Another example of the importance of minute amounts of certain elements is the use of cobalt. One atom of this metal is found in each of the complex molecules of the vitamin called B_{12}, having the formula $C_{63}H_{90}O_{14}N_{14}PCo$.

This is a ruby-red crystal whose absence in the body is the cause of pernicious anemia. Victims of this illness, until recently doomed to a slow death, are now easily saved by the addition of this chemical in very tiny daily doses. One millionth of a gram per day can sustain life. This bit of cobalt in our body, therefore, guards us against premature death.

Most plants also require at least 30 different elements, including extremely minute amounts of so-called trace elements such as boron and molybdenum. Without a trace of boron in the soil, for example, to the extent of only one part in several million, the bean plant slowly withers away. A trace of the metal molybdenum is needed by nitrogen-fixing bacteria. And so it is with the orange tree. If deprived of a trace of nickel to the extent of a mere 25 parts per million, the orange seedling is seriously stunted in growth. Minute amounts of the element manganese increase the vitamin C content of the tomato.

While most plants have no problem getting most of the elements they need from the air, water, and natural salts found in the soil, the three elements most frequently lacking in sufficient amounts are nitrogen, phosphorus and potassium. From every acre of wheat farmland each harvest takes two pounds of nitrogen. Every acre of corn land is robbed of 15 pounds of potassium, and every acre



of barley loses five pounds of phosphorus. This impoverishment of the land after years of supplying crop after crop must be overcome by putting back into the soil what the plants themselves have removed.

The plant must get its food dissolved in water, because only water with the various chemicals in solution can pass through thin leaves—or, more often, the delicate root hairs—by a process known as osmosis. Unless the food chemicals of the plant are served to the plant in water solution even the elements most vital to the life of the plant will never be available. Edwin E. Slosson, one of our great popularizers of science, once put it this way: "A farmer with his potash locked up in insoluble silicates is like the merchant who has left the key to his safe at home in his other trousers. He may be solvent, but he cannot meet a single draft. It is only solvent potash which plants can use."

From time immemorial men have improved their crops by adding fish scrap, bones, and animal and plant wastes to the soil. This practice had been handed down by the tillers of the land from father to son ever since the day some careful observer had noticed that the grass was greener and the corn taller around some buried bone, decaying fish head, or animal droppings. Dried blood, waste from slaughter houses, manure, and even human urine and excrement are still used to enrich the land in many parts of the world.

Only a little more than a hundred years ago a revolution started in man's thinking about how to feed a plant. The pioneer in this momentous event was the same Liebig mentioned earlier in this book. In conformity with the generally held belief at that time that some vital force was necessary for the manufacture of organic compounds was another doctrine that crops can thrive only on manure or other organic matter. Liebig felt certain this firmly entrenched idea was dead wrong.

He had the notion that the vegetable world could fix its own nutrients from the carbon dioxide gas of the air, the water in the ground, and any chemical compounds containing nitrogen, potassium and phosphorus mixed in the soil, and soluble in water. If these chemicals were

present in too small an amount or were altogether lacking, Liebig felt certain he could supply the deficiency by adding the vital elements in the form of ordinary inorganic chemicals such as soluble sodium nitrate ($NaNO_3$), potassium nitrate, or calcium phosphate. He told his farmer friends it was not at all necessary to foul the sweet earth with manure or smelly fish scrap to get good, healthy crops.

In 1840, to convince the scientific world and every farm hand who was interested, he started to test his unorthodox theory of soil fertility on a barren piece of land near Giessen, Germany. Year after year he continued pampering the soil of his experimental plot with pure inorganic mineral salts until he had finally turned it into as fertile a spot as could be found in all of Europe. He succeeded in proving among other things that "since plants assimilate potassium, nitrogen and phosphorus, these elements must necessarily be resupplied to the soil." It made no difference whether the elements were added in the form of inorganic chemicals or not. Others followed the path he had laid out and many famous agricultural experiment stations were established soon afterward in many parts of the world.

Millions of tons of nitrogen are removed from the soil each year by growing plants. About half of this amount is returned by nature, and by farmers in the form of fish scrap, manure and other organic wastes. The rest has to be added in other ways.

After Liebig had demonstrated the value of pure mineral substitutes of these plant foods, the farmers of the United States began to use inorganic nitrogen compounds, most of which they imported from Chile. Here in the northern part of the country the coastal mountains rise abruptly from the floor of the Pacific Ocean. Between this range and the westward slopes of the Andes Mountains, at elevations ranging from 4,000 to 9,000 feet, is a desert plateau where only occasional cloudbursts send water into the loose sandy soil. Most of this plateau has as low a rainfall as almost any desert on our globe. In certain sections annual rainfall is less than a single inch. Below this sandy soil is caliche, a rock containing between 50% and 75%

of sodium nitrate. This dissolves easily in water and may be used directly by plants. It is a perfect nitrogen food. This sodium nitrate was probably formed in this region by the action of certain nitrogen-loving bacteria, or accumulations of seaweed, bird droppings called guano, or other organic material. This salt gradually piled up, since it could not be washed away into the sea by the scanty rainfall that visited the area.

Here in the Andes was the greatest accumulation of concentrated nitrate deposits to be found anywhere, a circumstance which for many years gave Chile a world monopoly of nitrogen fertilizer. But not for long. For a new revolution in the world of chemistry was in the making. And when this change had been completed the Chilean nitrate industry declined rapidly. It still lives on, but it is only a shadow of what it was. Less than 5% of the 35 million tons of nitrate fertilizer used throughout the world comes from this source. It still brings about $40 million in foreign exchange annually to this South American country, mainly from our own farmers interested in high-value cash crops.

The nitrogen revolution had its origins in Germany. In 1913 Kaiser Wilhelm II, planning a war against England and France, called upon his chemists to help assure victory to German arms. They were assigned the task of making the Fatherland independent for her nitrogen needs from Chile, which in the event of war might very easily be shut off by blockade from German farms and munition factories. Sodium nitrate was not only a strategic chemical needed to grow food for Germany; it was also the raw material from which nitric acid became available for the manufacture of high explosives. No country could hope to win a war without it.

One of the chemists called in by the Kaiser for this job was Dr. Fritz Haber. He knew, as does any high school student now studying chemistry, that ammonia could be synthesized from its two constituent elements, hydrogen and nitrogen. Under heat and pressure these two gases combine in the proportion of one volume of nitrogen to three volumes of hydrogen to form two volumes of am-

monia gas. The chemical equation for this synthesis very simple. It is:

$$N_2 + 3H_2 \longrightarrow 2NH_3$$
(ammonia)

Now these two elements are available in unlimit amounts in any country, for nitrogen constitutes abo 78% of the atmosphere, and hydrogen can be obtain from ordinary water. But it is not as easy as the simp equation might lead you to believe. The ammonia g which forms is, for the most part, immediately brok down into its original elements. Only about 2% of t theoretical yield actually survives as a compound. It therefore, a very wasteful and costly process—100 ste forward and 98 steps backward.

Some way had to be devised to prevent most of t ammonia from decomposing and reversing the reactio It was a difficult problem that many had tackled a failed. Haber solved it. By determining just the right tem perature at which to unite the two gases, by calculati just the correct pressure which would give the largest yiel and by working out a method which would remove th ammonia gas as quickly as it was formed he succeeded raising the yield from a mere 2% to as high as 30% Though still very far from the theoretical goal, it was hig enough to make the process (now known the world ov as the Haber process) a practical one. This synthetic am monia could then be treated with some acid such as sulfur and turned into a salt, ammonium sulfate, which is an ex cellent substitute for the sodium nitrate buried high in th Andes.

Another German chemist, Wilhelm Ostwald, took on more forward step. Starting with this synthetic ammoni he found an inexpensive way of changing it into nitr acid, HNO_3, a key chemical in the making of munition of war. He did this by passing ammonia gas mixed wit air over heated platinum gauze. Without the platinu metal the two gases would be very reluctant to unite, an

the yield would be scanty. In the presence of the metal, however, the union is a quick and eager one and the yield very high. No matter how long the platinum powder is used, its weight is undiminished and it undergoes no permanent change. Evidently its mere presence does the trick. Such a chemical is known as a catalyst or catalytic agent. Just how it operates is still far from being solved. Yet many different catalysts are used today to hasten crucial reactions or improve the yield of some vital chemical process. They are the chemical parsons who unite the elements but remain uninvolved themselves in the marriage.

There are hundreds of different catalysts including the large number of enzymes. The action of a catalyst can be demonstrated by a simple experiment that anyone can perform. Try setting fire to a small cube of table sugar with the flame of a match. The sugar will char but not catch fire. Now flick a bit of cigarette ash on the cube of sugar and try again. This time the sugar catches fire rather easily and burns quite briskly. The cigarette ash acts as the catalyst, for it undergoes no permanent change during the burning, and can be removed intact after the sugar has been completely consumed.

The chemical victories of Haber and Ostwald sparked World War I. The Kaiser miscalculated and lost the war. Haber's successful synthesis of ammonia, however, met no such fate. It widened man's control over nature by making him less dependent for his raw material on far-away places where nature had strewn her bounty without regard to national boundaries or the special needs of the earth's human inhabitants. The synthesis of nitrogen compounds from the earth's limitless reservoirs of air and water was a bloodless revolution whose consequences touched the living and thinking of half the peoples of the earth.

The liberation of this country from foreign sources of potassium compounds needed in fertilizers followed a different course. The element potassium, like its close chemical cousin sodium, is a soft silvery metal which is extremely active. On exposure to air at ordinary temperatures, for example, it soon bursts into flame as it

combines vigorously with the oxygen of the air. W dropped into water, potassium reacts violently with evolution of much heat and the liberation of its hydrog Potassium compounds, on the other hand, are very sta and essential to the growth of nearly all plants. If, instance, potassium salts present in soil planted with tatoes are inadequate, the resulting sickly crop will sh very strikingly the potash hunger of this tuber.

In the early days when our land was still virgin and ve fertile, there was no potassium problem. In fact, for ma years the principal export of the American colonies a of the newly formed United States was crude potassiu carbonate. The American potash industry thrived un about the time of the Civil War, when very rich Eur pean deposits of potassium were dug from the salt min of Stassfurt, Germany. Here, in layers hundreds of fe thick, was an almost inexhaustible storehouse of solub potassium compounds mainly in the form of potassiu chloride. Other important sources were found later Poland, in Upper Silesia, and in France.

When World War I broke out in 1914 we were con fronted with a problem similar to the one that German had faced. We, too, had to find a way to become inde pendent of Europe for our potassium needs. Chile or an other part of the hemisphere was of no help to us in thi instance. We had to find sources of these chemicals withi our own borders.

Frenzied efforts were made in all directions. We gleane more wood ashes from land plants, and squeezed a littl more out of the ashes of kelp, a giant seaweed whic grows luxuriantly off the coast of California. We exploite the waste products of the sugar beet industry, and the by products of distillery slops. We scraped the dust from the flues of cement mills, and chipped off the outer surface o the linings of steel furnaces. In the sweat of the wool shorn from sheep we came across another source of potassium salts and utilized that, too. The green sands of New Jersey and other odd sources added more of the sorely needed salts of potassium. But we really could not meet our needs By 1926 we were still hungry for this fertilizer ingredient We were totaling, after all the sources we had tapped in

this country, only about 8% of our requirements. We had to go back to foreign mines.

At about this time we came across fairly large accumulations of potassium salts in the concentrated salt water of Searles Lake at Trona, California, and in the Salduro Marsh at Wendover, Utah. Finally, major discoveries were made in both Texas and New Mexico. In the hunt for oil we came across a rich mine in the lake beds deposited on the floor of the Permian Sea a million years ago. This spot is now Carlsbad, New Mexico. Our engineers and chemists attacked this ancient cache with the avidity of a pack of hungry bears. Two hundred miles of tunnels were bored through this region, and mountains of sylvite and polyhalite, compounds of potassium, were dug out of it. By 1941 we were actually for the first time independent of foreign supplies of this element. In the quarter of a century between World Wars I and II, the combined effort of the federal government and private industry succeeded in increasing our annual output to more than a million tons. Ten years later, this skyrocketed to more than two million tons, and today we are actually exporting this precious commodity. The Carlsbad mines account for 90% of our domestic output.

There is an even richer source of potassium all around us, but the key to unlocking its treasure is still hidden from us. Feldspar ($KA1Si_3O_8$), very widely distributed in this country, is a compound containing one potassium atom in its molecule. During weathering it changes to common clay. Feldspar is insoluble in water and hence unavailable as a direct plant food. No chemist has yet devised an inexpensive method of forcing this mineral to surrender its potassium holdings in a form which the plant could utilize. The challenge is still here and a fortune awaits the man who solves it.

Our chemical suppliers are learning to compound fertilizers of many kinds to meet the peculiar requirements of each kind of crop grown in various types of soil. To save freight charges these fertilizers are being offered to farmers in a highly concentrated form. Some contain only two of the usual elements, namely nitrogen and phosphorus, or nitrogen and potassium. Potassium nitrate (KNO_3),

for example, is rich in both potassium and nitrogen. occurs naturally in the topsoil of certain sections of Ind Iran, and other countries, but the supply is not so great that of sodium nitrate. It is one of the three ingredien too, of gunpowder. From the time this explosive began be used in Europe, the constant warring of nations led a great demand for potassium nitrate.

Among the very first papers communicated to the En lish Royal Society was one that dealt with the manufactu of this salt. Its author declared, "The only place whe saltpeter [potassium nitrate] is to be found is in stabl and pigeon houses." The East India Company importe nitrate from India as early as 1625. In France and Ge many niter plantations sprang into being. These we heaps of organic material mixed with wood ashes ar other alkalies. The putrefaction that went on in this ga bage produced more than smells; it formed valuable po tassium nitrate. Up to the time of Lavoisier, officials o the French government had been accustomed to searc for potassium nitrate in wastes, in compost heaps, and i the cellars of private houses. They confiscated it, both t help supply the needs of the country and to prevent it use in insurrections. But shortly before the French Rev olution, Lavoisier, as controller of munitions, abolishe this practice of confiscation and, at the same time, in creased the supply of this salt by developing better meth ods of manufacture.

Today, the chemist makes potassium nitrate from th more abundant sodium nitrate, and it is still widely use as a fertilizer. One such product, for example, prepare for the growing of sugar beets, is a 4-12-6 fertilizer. Thi means 4% nitrogen, 12% phosphorus (oxide), and 6% potassium (oxide).

Mineral mixtures containing one or more trace el ements are also available now for direct application o mixed with fertilizers to correct special mineral deficien cies in soils. Some elements are being added directly t the leaves rather than through the roots. Nutritional spray such as "Nu-Z" containing several compounds have bee introduced for direct foliage feeding. During the last fe years millions of tons of nitrogen in the form of solution

of ammonia or other nitrogen compounds have been applied to the leaves of plants, and other millions of tons of ammonia have been injected directly into the soil by means of specially designed machinery, or added to irrigation water.

The fertilizer business is one of our basic industries. At the opening of the present century American farmers scattered a mere three million tons of chemicals on our farms. Sixty years later we were feeding our soil with more than 30 million tons of fertilizers, at a cost of more than a billion as compared with only $50 million in 1900. Even though there has been an even more spectacular increase within the last ten years, a three-fold one, there is still plenty of room for expansion, for it has been estimated that only 25% of our total crop land receives today any application of commerical fertilizer at all.

This accelerated consumption of commerical fertilizers by American farmers is the result of the proved fact that their use pays off. Our farmers have increased crop yields far beyond the cost of the fertilizers they purchased. On the same land we are producing 42% more food than we did 15 years ago. Total corn production, for instance, rose 58%, wheat 31%, cotton 43%, and potatoes 111%. This, in spite of the fact that our farm population has fallen. It must be remembered, of course, that about one third of this increase must be attributed to better use of soil and water resources, crop rotation, and especially to the growth of mechanization on the American farm.

Yet this spectacular increase could never have been achieved even with the lavish use of the best fertilizers if it were not for the army of man-made chemical soldiers who guarded the growing plant from the moment it was placed in the ground as seed to the time it was marketed. For ravenous hordes of both insects and parasites menaced its life. A sizable part of the insect world, 7,000 different types of pests, have been in a state of constant warfare against the plants that feed us. They still destroy crop values amounting to about $4 billion each year in this country alone.

This insect world, which outweighs all other living things including man, was a heartless adversary, and the

farmer cried out for relief. The synthetic chemist answered the call with a stream of new chemicals concocted in his test tubes and flasks. It was not easy to destroy the insects. Their manifold adaptations made many of the insects the aristocrats among living things. For as one scientist put it "Man is but a creature of the last twenty minutes or so compared with the cockroach that hides behind the kitchen sink but who can point his antennae to the coal in the hod and say, 'When that was being made my family was already well established!' "

Tough skeletons that resist the action of even acids and bases, digestive systems that can effectively assimilate anything from pepper, beer, perspiration, and mustard plasters to mummies, urine, and old manuscripts, and springy legs enabling them to jump distances which would make it possible for man, in comparison to his own weight, to reach the moon in a few hops, these qualities help to explain their resistance to extinction. Structural and color characteristics in walking sticks and measuring worms which closely resemble the twigs and foliage on which they live, smoke-screen apparatus which goes into immediate action when the bombardier beetle is in danger, reproductive powers which would enable one single plant louse to produce enough progeny in one season to outweigh the earth's human population fivefold, heat-resisting powers which make it possible for larval midges to live in pools at 120° F, polyembryony, or the development of thousands of adult insects from one solitary egg—these are but a few additional reasons why insects still hold dominion on our earth.

Until fifteen years ago most insecticides were obtained from natural sources. They consisted mainly of inorganic material such as sulfur and lime-sulfur sprays, copper compounds such as copper sulfate and Bordeaux mixture, arsenic salts like Paris green and calcium and lead arsenates, several fluorine compounds such as cryolite and sodium fluoride, as well as a few organic substances like nicotine sulfate, petroleum distillates, soap sprays, rotenone and pyrethrin. In 1955 we obtained from Africa, Japan, Ecuador and Brazil as much as 100,000 pounds of pyrethrin powder extracted from millions of pounds of the

pyrethrum flower, a plant resembling a large daisy. But many new chemicals had to be hand-tailored to take into account the resistance, behavior patterns, and eccentricities of thousands of different insects. The chemist's highly developed brain was pitted against the uncanny instincts of the insect plus the incredible ability of these creatures to adapt themselves to new situations including chemical. It was touch and go for many years. But the synthetic chemist is gradually winning the battle.

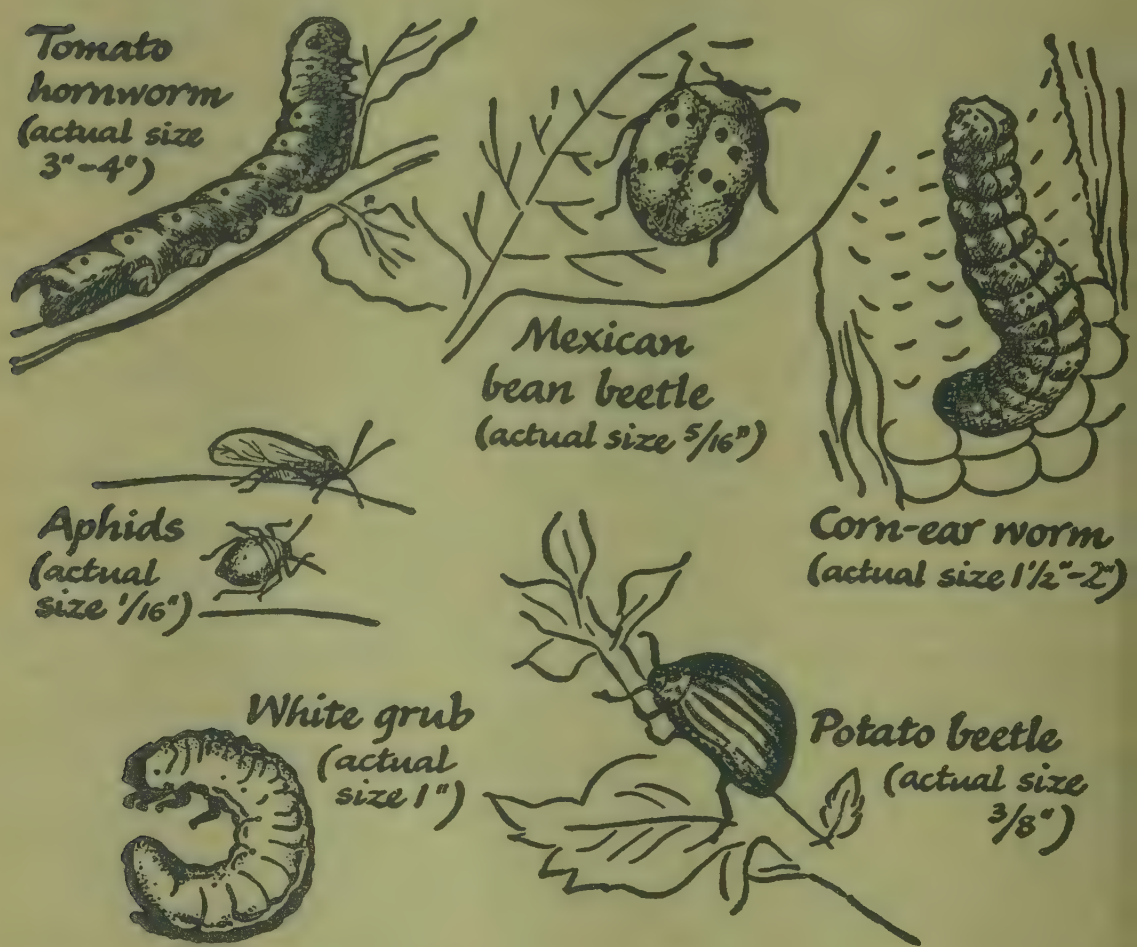
He has put together scores of synthetic compounds, including synthetic pyrethrin-like chemicals and made them available in tremendous quantities. Almost a billion pounds of formulated insecticides were produced in this country in a recent year, including 100 million pounds of DDT and 30 million pounds of 2,4-D. With these destroyers the American farmer is fighting the insect pests and other farm marauders on many fronts.

Consider one of the fronts—the tomato sector of this war. Specially designed insecticide molecules are sprayed on the young plant as soon as it breaks through the surface of the soil in search of sunlight. This is the man-made toxaphene dust, a chlorinated hydrocarbon which protects it from the cutworm pest. When the tomato starts to produce its fruit, a 2.5% mixture of another similar synthetic chemical of aldrin stops the darkling beetle dead in its tracks. Then the heavy artillery of DDT, still another chlorinated hydrocarbon, greets the tomato fruitworm with murderous salvos. Finally a 2% synthetic parathion dust, an organic compound whose chemical name is diethylparanitrophenylthiophosphate holds the leaf miners at bay and prevents them from multiplying on the plant. Left alone to follow their instincts they would destroy the tomato plant in short order.

In some cases, the plant is protected by the chemist even before it reaches the open air. Seeds are treated (pelleted) with special chemicals before they are placed in the soil. Corn seed, for example, is treated with benzene hexachloride to protect it against the wireworm. The chemist tricks the insect in other subtle ways. For example, he has constructed a phosphorus-containing organic compound which is applied to the seed before planting. As the plant

grows this chemical, harmless to the plant, gets into its sa stream. When the plant emerges above ground any aphi or mites that start sucking the juice of their quarry do s for the last time, for the insecticide in the sap is deadl to them.

When Joel promised, "I will restore to you the years tha the locust hath eaten," he might have included a few othe former crop destroyers—the corn earworm chewing hi way through the living plant with the power of a mea


Tomato hornworm (actual size 3"-4")
Mexican bean beetle (actual size 5/16")
Aphids (actual size 1/16")
Corn-ear worm (actual size 1½"-2")
White grub (actual size 1")
Potato beetle (actual size 3/8")

grinder, the codling moth tunneling through the apple with the effectiveness of an auger bit, the Mexican bean beetle ripping its vegetable prey with sharpened scissors, and the tiny aphids sucking the life juices out of their victims. The synthetic chemist has fought these, too, to a standstill.

Insects are by no means the plant's only enemies. The growing plant is also at the mercy of other plants. Weeds struggling for a place in the sun and for food and water to fatten on are no respecters of the rights of neighbors.

They laugh at our notions of the sacredness of private property. They clog irrigation ditches, muscle in wherever they feel like, and choke, steal, and destroy the lives of perfectly innocent fellow plants and even farm animals. In the United States alone weeds reduce the nation's annual crop value by a whopping $3 billion, and also pile up time cards of millions of work hours of backbreaking, manual weeding.

Here again the creative chemist has stepped in to aid the farmer. Long years of research and tens of millions of dollars, for it costs as much as $1.5 million to develop a single new effective herbicide, have been spent to get these battalions of botanical bandits under control with newly designed chemicals that aim directly at the weed and are harmless to the food crop. For example, discovery of the weed killing properties of the chemical 2,4-D previously mentioned may be ranked among the most important farm discoveries of our time. Its chemical name is dichlorophenoxyacetic acid and its molecule, again, contains that ubiquitous benzene structure.

2,4-D owes its power to the fact that it is a growth stimulator or plant hormone. The synthetic chemical was patented in 1943 when it was found to increase the growth of plants when applied in minute amounts. Later, larger doses were tried by chemists on the herbicide front. It was found that this treatment killed the plant, which had proceeded to use up its own food supply too rapidly and then starved to death. Fortunately, too, this chemical is selective in its action. It attacks broadleaved weeds such as ragweed and poison ivy with vigor, but leaves the thin-leaved grassy plants, including the cereals, strictly alone. A water solution of the sodium salt of this compound is applied as a spray over millions of acres of our cereal belt.

A close relative of this herbicide has also been synthesized to help banish chopping, hoeing, hand pulling, and mowing. It is 2,4,5-T, whose chemical name is trichlorophenoxyacetic acid. Had the gardener in *Richard II* had these modern chemicals at his disposal his words

I will go root away
The noisome weeds which without profit suck
The soil's fertility from wholesome flowers

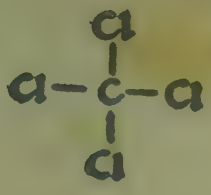
would not have been idle ones, for the modern farmer h done wonders with them. In Oklahoma, for example, has controlled the sand sagebrush, in Texas the mesquit in a dozen other states the wild mustard, and in Nor Carolina the bluemold of tobacco. Ammate (ammoniu sulfamate) is another herbicide that has been added to t weapons of the farmer. It goes after many weeds, includi poison ivy, with real enthusiasm. Some weed killers suc as Premerge, another complex carbon compound, are no applied when the soil is first prepared for planting suc diverse crops as beans, corn, oats and peanuts. They ki the young weed plant underground before it can emerg

The widespread use of these and other weed destroyer such as sodium chlorate, carbamates, amino triazole diuron and endothal has, to be sure, robbed our country side of its blaze of color, as the brilliant asters, butterfl weed, and sumac fell victims to the chemical war. But thi is a small price to pay in the relentless fight of the farme to save his crops.

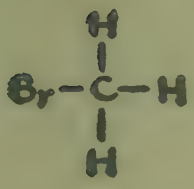
Crops present other serious problems which our chem ists are trying to solve. They are heir to more than si thousand different bacterial and virus diseases, and hav to survive the infiltration of one or more of the severa thousand plant parasites known as fungi. The destructive ness of fungi totals as much as another $3 billion eac year. Chloranil and newer chemical fungicides with such impossible names as N-trichloromethylthiotetrahydroph thalimide and tetrachloro-p-benzoquinone are being syn thesized to cut this loss. Antibiotics such as streptomycin have been called up for the fight, and compounded fer tilizer and pesticides are coming into more general use.

Even after our crops have run the deadly gauntlet o insects, weeds, bacteria, viruses, and fungi in the field they are still at the mercy of many enemies lurking in storage bins. For example, weevils and beetles can have a gay time with grain stored away for future use, unless the farmer has taken steps to protect his product. To help in this final battle for survival the chemist appears once more and presents the farmer with relatively simple molecules. The most commonly used and effective of these fumigants are

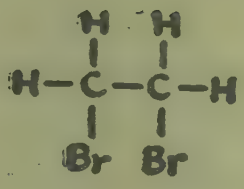
substitution products of some simple hydrocarbons, such as carbon tetrachloride,



methyl bromide,



and ethylene dibromide,



The chemist has endowed the farmer with still another gift—new, nonfertilizer, man-made chemicals which are great time-savers. They are organic compounds which, when applied to a ripened crop, cause the leaves to fall off from certain plants (such as cotton and soybean) prior to harvesting, making this mechanical operation much faster and cheaper. They are known as defoliants. One of these newest chemical "hired hands" of the farmer is a compound he has known and used for a long time as an excellent nitrogen fertilizer—calcium cyanamid. In California and Arizona, more than half of the cotton raised is chemically defoliated. Magnesium chlorate is another cotton defoliant.

The chemist is also attempting to regulate the maturity of different plants so that portions of the growing crop will mature at different times, thus enabling the farmer to spread the harvesting and processing time of his farm prod-

ucts. Naphthalene acetic acid, for example, has been su cessfully used to do exactly this with the pineapple cro The chemist is at work, too, on the construction of chem icals that will prevent the premature falling of fruit apple orchards and orange groves all over the land. An he is even hoping to find effective molecules that will pr vent the costly sprouting and spoiling of potatoes an onions while in storage. With modern fertilizers, powerf insecticides and fungicides, chemical weeding, defoliatio and the very important mechanical harvesting, the "chem ical farmer" in America can often do ten times as muc work today as an unaided farmhand did fifteen years ag And he can produce almost twice as much food and fibe

The new synthetics of the chemist are also benefitin those who raise our animal food. A variety of new chem icals for the improvement of animal nutrition and healt are now available. Sales have approached one quarter o a billion dollars a year in the United States alone. The are helping to cut down our annual loss of more than $ billion due to attacks of parasites, insects and disease o farm animals and animal products. Hens lay more egg and cows give more milk when they are free of disease are not tormented by pests, and are fed on a scientific diet For example, with the new insecticides such as Marlat used as a dip and as a spray, the control of blood-sucking hornflies alone has increased the milk supply by more than 10%.

By scientifically fortifying the feed stocks of his animals with both natural and synthetic products of the modern chemists, such as vitamin B_{12}, body-building amino acids (like methionine), phosphates, and other chemicals the farmer has increased the productivity of his herds and flocks. Small supplements of antibiotics have improved the health and increased the weight and products of farm animals, just as the synthetic vitamins of the chemist, when added to margarine, milk and flour, have improved the health of the farmer himself.

This latest scientific development among farm animals started in 1950 as the result of one of those "lucky accidents." Hogs and poultry had been fed on a diet enriched with a small amount of impure vitamin B_{12}. It was

noticed that these animals grew faster. No one knew why. An investigation was started. Stockfeeds had been enriched with vitamins A, D, E, and K, amino acids, vitamin B_{12}, and other chemicals. It was found that the B_{12} fed to the animals was one of the by-products of a manufacturing process. It had come from the fermentation vats in which antibiotics such as streptomycin were being made. The same mold that produces streptomycin also manufactures vitamin B_{12}. This vitamin, B_{12}, was shown to contain a trace of the antibiotics as an impurity. It was apparently this small amount of antibiotic added to the animals' diet that was the cause of the more rapid growth and heavier weight. How the antibiotic produces these highly desirable effects is not completely understood, but some believe that it prevents disease in the intestinal tract of the animal. This condition accelerates the whole digestive process, and enables the animal to assimilate more nutrients.

The first large-scale introduction of this new practice was in 1952. Pigs were given terramycin in their diet. They reached their market weight of 200 pounds fifty days earlier than heretofore, and saved the farmer a great deal of money and work. Chickens, too, responded to the new dish. As little as two grams of penicillin in a ton of chicken feed produced three-pound broilers in nine weeks instead of the usual 11 weeks at a cost of less than one dollar. Calves, too, brought up on stock feeds enriched with tiny percentages of antibiotics, grow as much as 10% faster and become 10% heavier. So successful has this procedure been that within a short time after its introduction almost 15% of all the tetracyclines, bacitracin, terramycin, penicillin, aureomycin, streptomycin, and other mold drugs manufactured in this country was consumed by farm animals.

Some antibiotics such as aureomycin (chlorotetracycline) and terramycin (oxytetracycline) are also being widely used to prevent the spoilage of uncooked poultry, especially by America's leading chain food stores. Canada is using antibiotics in its fish industry for the same purpose. They stop bacterial growth responsible for food spoilage.

In addition to improving crops and livestock, insecti-

cides protect millions of people. These chemicals includ repellents such as sulfur and turpentine, stomach poison such as arsenic compounds which are used against beetle and other chewing insects, and body-contact poisons whic attack sucking insects, such as plant and body lice. Th world's most spectacular and effective contact insecticid is the familiar DDT whose chemical name is dichloro diphenyl-trichloroethane. It is a white crystalline com pound which was first synthesized about 80 years ago For more than half a century it remained just anothe benzene derivative among tens of thousands of other car bon compounds. Then suddenly in 1939 a Swiss chemist Paul H. Mueller, found it to be an extremely effective insecticide. Its first dramatic act was to save the Swis potato crop which was severely threatened by the Colo rado potato beetle. It did a spectacular job.

But it was to be called soon after on a lifesaving mission involving millions of human beings. During World War II it was adopted as the active ingredient of the most ef fective de-lousing powder ever dreamed up. Before its advent it was said that front-line soldiers were never with out lice. Lice in themselves are not pleasant fellow travel ers, and the fact that they carry typhus fever makes them more dangerous and deadly than bullets. DDT's effec tiveness as a killer of lice was found to be unparalleled. After one application, underclothing remained louseproof for as long as eight weeks. In a typhus epidemic in Naples in 1943 a million people were dusted with it and the epi demic was wiped out in a few days.

DDT also kills the mosquito that carries malaria. It did heroic work especially in Italy and Greece during World War II. In the decade that followed its introduction in Italy it saved five million lives. There were 400,000 cases of malaria in Italy alone in 1945. Six years later there were less than 400. Mueller was awarded the Nobel Prize in physiology and medicine in 1948. There is still plenty of work ahead for DDT. In Asia, the Near East, and in equatorial Africa it has been estimated that 300 million people are still malaria-infected. As many as three million lives could be saved there each year by the proper utili zation of this new weapon of the synthetic chemist.

The chemist had won many battles in this field but he dared not relax. After the first spectacular results of DDT it was noticed that insects formerly an easy prey to this chemical began to show signs of immunity. Even larger doses seemed to have little effect. Reports came in to show that body lice in Egypt and bedbugs and houseflies in Italy had built up strong defenses against DDT. Chlordane, another chlorine derivative of a hydrocarbon, seemed to have lost its terrific punch against the Texas cockroach.

What really happened was this. Each newly introduced insecticide slew millions of susceptible insects. But there were some insects among them who were naturally immune against the chemical enemy. These peculiar variants of the insect species kept multiplying in the midst of the holocaust and passed on their natural immunity to their millions of offspring. Soon all the susceptibles were gone, and in their place was an equally large army of insects who thumbed their noses at the chemists' insecticides. So the chemists had to go back to their laboratories to hand-tailor new chemicals that would destroy those who were immune to DDT or chlordane. They were faced with the task of creating new chemicals faster than the insect world could adjust to them.

Mountains of new and improved chemical fertilizers, thousands of tons of synthetic insecticides, herbicides, fungicides, fumigants, defoliants, and soil conditioners, most of which came to the farmer within the last twenty-five years, have produced a chemical revolution on the farm as important as the change from beast to tractor. It is as dramatic a transformation as has occurred in any similar period of time in man's struggle to keep himself alive.

6 New Metals for the New Age

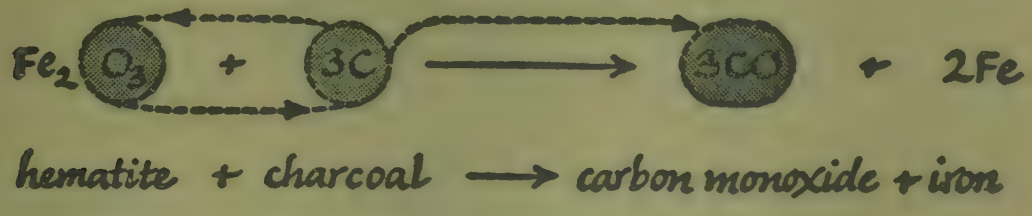
THE OX, the horse, and finally the mule have all but disappeared from our landscape. Their muscles were too weak and their pace too slow to cater to the wants of an ever-increasing population demanding more and better things. Locomotives, automobiles, tractors, airplanes and a myriad of other versatile machines were fashioned out of iron and other metals. Today 120 million tons of iron and steel are made each year in the United States from ore torn from the earth—1400 pounds for every man, woman and child in America—to satisfy the needs of our highly industrialized society. The total annual production of iron in the Colonies at the time of the birth of modern chemistry could be turned out today in just a few short hours.

There was a time, perhaps 5,000 years ago, when man had no iron, when the only metals available to him were copper, gold and silver. These were the earliest known metals because they were found in the free or chemically uncombined state. The red metal copper, for example, was present in the outcroppings of rocks, and all that was needed was the physical strength and patience to cut it away from the rest of the hard stone. The native copper was then easily hammered into weapons or farm implements or fashioned and polished into ornamental objects.

The Copper or Bronze Age, therefore, preceded the Iron Age, for iron occurs on earth only chemically combined with other elements. The Egyptians and Assyrians were the first metallurgists. Wrought iron was known at least 4,500 years ago. Iron was common in Egypt 4,000 years ago, and was probably imported from the Hittites. It was mined most frequently as an oxide such as Fe_2O_3, or hematite. We have no record of how man first hit on the idea of heating the iron oxide with charcoal to a high temperature to release the iron from the oxygen combined with it. In any case, the discovery was certainly an ac-

cident that occurred before the dawn of recorded history. It could not have been based on any chemical knowledge.

What actually happens when iron oxide is heated with charcoal (carbon) is that the carbon unites with the oxygen of the iron oxide, according to the following chemical equation:

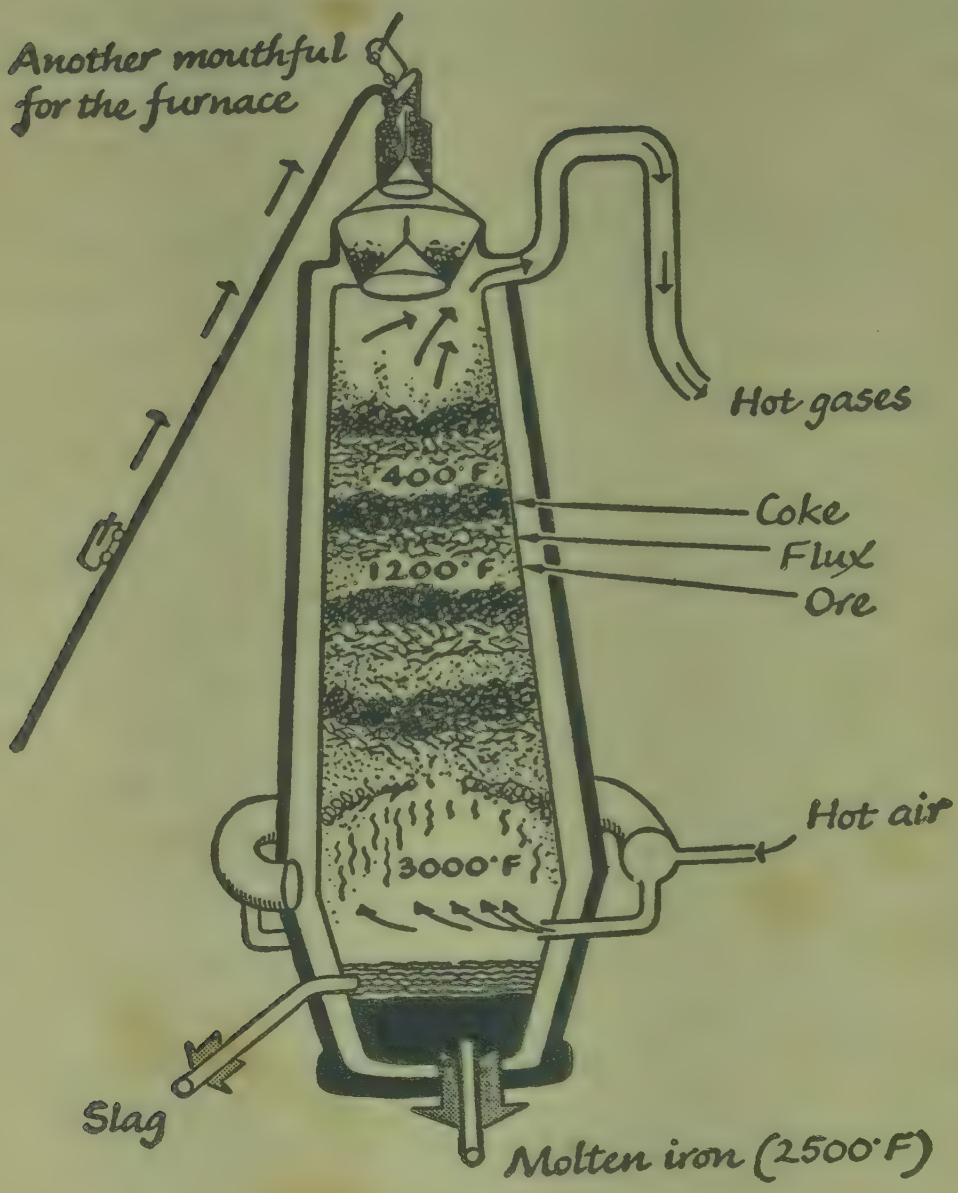


The chemical removal of oxygen from an oxide is known as the process of reduction. It is one of the three most common methods of extracting metals from their ores. Carbon, in this case, is called a reducing agent.

The enclosure in which the reduction of iron oxide is carried out is known as a blast furnace. Today's 110-foot-high cylindrical blast furnace is the product of at least six centuries of development. It is constructed of steel plates lined inside with heat-resisting brick to withstand the high temperatures reached. The crude bellows of bygone days which forced air into the furnace have been gradually replaced by powerful pumps that force into the furnace blasts of hot air from three or four tall cylindrical stoves through pipes or tuyères (pronounced "tweers") located near the bottom of the furnace. There are about 260 blast furnaces in the United States today. The world's largest blast furnace was completed in 1955. It was built in the Middle West and stands 250 feet high.

Coke from coal has replaced wood charcoal as the reducing agent in the smelting process. As the reduction of the iron ore proceeds, a thick, molten, lavalike liquid, known as slag, floats to the surface of the molten iron. Slag consists of the impurities in the iron ore combined with the flux such as lime which is part of the charge dumped into the furnace. The slag is poured away from the iron about every four or five hours, just before the free iron is tapped from an opening at the bottom of the furnace. A blast furnace operates continously for many

months and is shut down only for repairs, lack of orders, or occasional strikes. A typical blast furnace costs as much



as $10 million and produces about 1,000 tons of iron daily.

The iron that pours out of the blast furnace is called pig iron. The name is derived from the fact that in the early days of molten iron flowed into metal forms which resembled a litter of feeding pigs. Pig iron is not pure iron. It contains about 4% carbon (from the coke used), and smaller amounts of compounds of sulfur, phosphorus, manganese, and silicon. These impurities account for its gray color and its brittleness. It melts at about 1150° C. (The temperature of the tip of the flame of your gas range burning natural gas is somewhat higher.) About 7% of

the output of pig iron is shipped in solid form to foundries for the making of a variety of castings, sash weights, sewer pipes and radiators.

Until the fourteenth century practically all the pig iron made was changed to wrought iron before use. Wrought iron is almost pure iron containing only about 0.1% of carbon. It is relatively soft, tough, and resists shocks and strains rather well, as well as atmospheric corrosion. It is the kind of iron still used to a small extent to make chains, anchors, temporary magnets, and wrought iron furniture and decorative pieces.

Practically all the rest of the pig iron that pours out of our blast furnaces is changed at once into steel. This is the form of iron most familiar to you. Steel, too, has been known and used for centuries. It is believed that a tribe of people living in the southeast corner of the Black Sea some 3,500 years ago made the first steel used by man. They discovered that when wrought iron is heated in charcoal it develops a very hard (steel) exterior while retaining a softer (wrought iron) interior—a perfect material for sword blades. The Saracens inherited this discovery and made Damascus blades chiefly for weapons in the war against unbelievers.

The manufacture of iron in America was started very early in our history. In 1628 some iron ore found in bogs and swamps was converted into pig iron at Saugus, Massachusetts. Thirteen years later, John Winthrop, Jr., went to England to form "a Company of Undertakers for the Iron Works," which he established in Saugus, and to bring back machinery and a few workers skilled in the making of both pig iron and wrought iron. By 1700 about a dozen ironworks were in operation in the Colonies, turning out iron pots, stoves, skillets, and wire for nails. In 1725 the first American steel was made by packing iron bars with coal in a furnace and heating the mixture for as long as a week. By 1775 eighty blast furnaces turned out 30,000 tons of cast iron. This represented about 15% of the world's output for that year.

Both wrought iron and steel had been made for hundreds of years in small batches by a few skilled workers using a very slow and costly process. The demands for

steel were very limited in those days and no drastic change in its manufacture was needed. However, the invention of the rifled cannon, the locomotive, and other mechanical devices brought an immediate and unprecedented demand for huge quantities of steel. At just about the time when the nineteenth century was passing its midpoint the shortage of steel was aided by a great invention.

William Kelly, a Pittsburgher living in Kentucky, got the notion that ordinary air blown through molten pig iron would burn out most of the impurities in the pig iron. This would give him a lot of steel quickly and inexpensively. He figured that the blasts of air, instead of chilling the hot molten pig iron, would actually raise its temperature to the boiling point by oxidizing or burning out its carbon and other impurities. This was a rather fanciful idea according to the steel men of his time. He was ridiculed wherever and whenever he mentioned it. His father-in-law questioned the man's sanity, and had a doctor examine him.

Kelly, however, was stubborn enough to go right on with his plans, and in 1851 he gave a public demonstration of his novel process. An eye witness reported the scene as follows: "We saw a vessel that had a mouth open at one side and near the top. The whole was shaped something like an egg. We saw molten metal poured into the vessel. Then Kelly turned on a blast of cold air. The vessel set up a roaring noise, and fire belched furiously from its mouth, making many colors. But only for a few minutes. The noise and fire died down. We then saw a blacksmith take a small part of the iron which had cooled, and contrived and threw at the feet of the amazed spectators a perfect horseshoe. No one laughed at Kelly now."

While Kelly was working to improve his invention Henry Bessemer in England was discovering the same process independently. During the Crimean War he had made the blueprints of a new type of cannon but could not find an iron strong enough to withstand the high pressures of the expanding gases that were released from the explosion of the chemicals in his new weapon. This led him to research in steel. In 1856 he finally solved the problem by inventing a steel converter and obtained a patent on

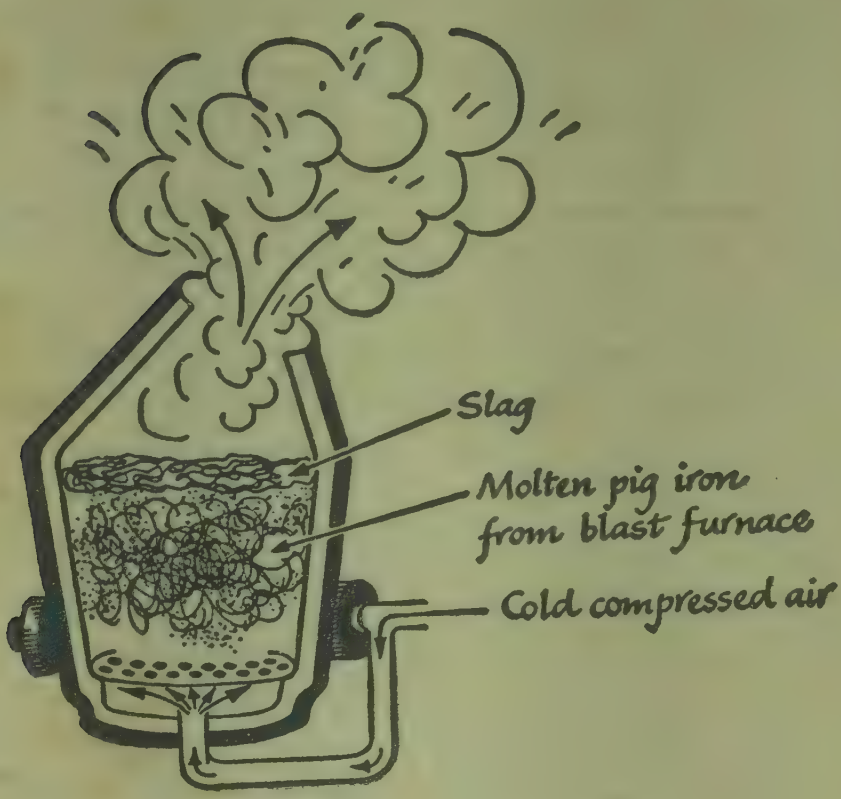
his own process. Then Bessemer built an even more efficient furnace than Kelly could offer, and bought out Kelly's patent for the manufacture of steel.

In 1866, at the age of 53, Bessemer was knighted. This honor came to him not, as might be expected, for his historic invention of a new process for making steel but rather for a suggestion he had made when he was twenty years old. He had recommended an ingenious improvement for preventing the re-use and counterfeiting of seals and stamps used on government documents.

The world was waiting for inexpensive and abundant steel. Almost overnight the whole iron industry was revolutionized. The first Bessemer furnace or converter set up in the United States was located at Troy, New York, in 1864. The new process completed in less than ten minutes what the old, cumbersome, and costly method of manufacture took a whole month to accomplish. The outmoded puddling furnaces in which wrought iron was cooked were almost entirely scrapped. Steel replaced wrought iron everywhere. Tons replaced pounds in steel output. By 1870 steel production had forged ahead so rapidly that it caught up with wrought iron. By 1880 we were making one million tons. By 1914 steel production reached 40 million tons. In 1960 steel capacity in this country had mounted to the unprecedented figure of 148 million tons, whereas our output of wrought iron is less than one per cent of this figure. World production of steel is about 350 million tons, of which Russia accounts for about 65 million.

The present-day Bessemer converter used in the United States is a pear-shaped steel pot about 10 feet in diameter and 20 feet deep. It is lined with clay and heat-resistant bricks composed mainly of pressed sand. Fifteen tons of a fiery broth are emptied into the Bessemer converter from a container holding the molten pig iron from the blast furnace. Through this boiling mass of liquid iron, blasts of cold air are forced under pressure through holes in the bottom of the converter. The oxygen in this air combines chemically with the carbon and silicon impurities of the pig iron. The carbon forms carbon monoxide gas, which burns away at the mouth of the converter. The silicon

forms silicon dioxide, which accumulates as slag floating on the surface of the molten steel.



As the blow continues, the carbon impurities keep burning. A roaring boil is heard coming from inside the cauldron of iron. The carbon monoxide flame lights up the air, reaches a height of about 30 feet, and countless flying sparks of metal and slag add to the brilliant spectacle visible for miles at night. In a few minutes impurities have been burned out of the pig iron, the flame flickers and contracts. The show is over. This is the signal for the operator to stop the blast of air by turning the vessel over on its side.

The iron at this point contains some dissolved iron oxides but practically no carbon, and if allowed to cool and solidify without further treatment it would be spongy and weak. So a calculated weight of both carbon and the metal manganese are dumped into the seething liquid. This practice was first suggested by an Englishman, Robert F. Mushet. He introduced manganese in the form of ferromanganese or spiegel, alloys of iron, manganese, and carbon to the molten iron in the Bessemer converter, and

really made modern commercial steel for the first time. He received a patent for this in the same year that the Bessemer converter was patented.

The carbon gives the steel the desired hardness, flexibility and corrosion resistance. The manganese strengthens the steel further by combining with the oxygen of the dissolved iron oxides and, in addition, produces a more desirable manganese-steel alloy. An alloy is a mixture of two or more metals or of metallic and nonmetallic elements which dissolve in each other when molten, and do not separate into distinct layers when the molten mixture cools and hardens. Ordinary steel, which is usually a mixture of iron, carbon, and manganese, is, of course, the commonest alloy. Bronze of which our pennies are made is an alloy of copper, tin and zinc.

Whereas there is only a handful of metals in common use, the number of useful alloys runs into the many thousands. Steel is a cosmopolitan and versatile alloy. Add one or more special metals to it in just the right proportion and it acquires almost any property you want. Give it some chromium metal, for example, and it changes to the familiar and widely popular stainless steel used for kitchen utensils or the outer surface of a towering skyscraper. Throw a carefully weighed amount of the metal tungsten (now also called wolfram) into molten steel, and out comes a precious steel alloy with an extremely high melting point. Tungsten steel is very hard and stays hard even when red hot. The speed of boring and cutting machines was previously limited by our inability to keep the cutting tool cold, for as the tool became heated it lost its keen edge. Tungsten took care of that problem.

Many steel alloys contain nickel. Invar, which expands very little on heating and is, therefore, used for lead-in wires in electric light bulbs, is a steel alloy containing 35% nickel. Several nickel steels are much more magnetic than iron and are therefore used in radio and TV receivers and in magnetic tape recorders. Molybdenum and vanadium steels are used to give resilience and strength to axles, springs, wrenches and rails under the impact of severe shocks and strains. Silicon improves the magnetic quality of steel, and niobium steel has been developed for high

temperature resistance in reactors and engines. Ot
alloys include nickel chrome steels for armor-plate; col
steel, which is resistant to corrosion at high tempentu
for gas turbine tail cones, combustion chambers, and
planes; and manganese steel for the jaws of rock cru
power shovels that bite into rock, brake shoes tha
trains, and burglar-proof safes.

The Bessemer process was by no means the last
in steel manufacture. It had one serious drawba
could not successfully handle pig iron containing
than a trace of the phosphorus compounds. Phosp
like carbon, is oxidized in the Bessemer furnace duri
blow, to be sure, but the phosphorus oxide thus f
will not leave the molten iron and join the slag wh
drawn off. Five years after the invention of the Bessem
converter, Karl Wilhelm Siemens, who left his native G
many to become a citizen of England, patented the
called open-hearth furnace for treating pig iron. In 18
the first of these furnaces was built in the United Stat
and today 911 of such furnaces account for most of t
steel manufactured in this country. Only about 3% of o
steel is now made by the Bessemer process here, and abo
8% in electric induction furnaces where the raw materi
of specially selected scrap steel and iron ore is heated-
sometimes in a vacuum—by means of electricity. Sma
batches of about five or ten tons of special steels are mad
in these huge teakettles.

Generally, several open-hearth furnaces are built end
end, like houses in a row. The average present-day oper
hearth furnace, as large at least as an eight-room hous
contains a shallow, oblong steel basin about 50 feet lon
20 feet wide, and three feet deep, lined with limestone an
encased in heat-resistant brickwork. Molten pig iron
poured from a ladle into the hearth or basin, and a larg
charging machine with a long steel arm empties boxload
of the rest of the raw materials consisting of limestone
some iron ore, and a large amount of scrap iron derive
from old cars, motors, and farm and other machinery
Burning gases and hot air enter the furnace at one end
are deflected downward from the brick-lined roof of th
furnace heating the charge just as a huge torch would do

A number of chemical changes result. First, the carbon present in the pig iron is burned out and disappears in the form of carbon monoxide gas:

$$2C + O_2 \longrightarrow 2CO$$

carbon + oxygen ⟶ carbon monoxide gas

The iron oxide ore provides additional oxygen to rid the pig iron of its undesirable carbon impurity according to to this equation:

$$Fe_2O_3 + 3C \longrightarrow 2Fe + 3CO$$

iron oxide + carbon ⟶ iron + carbon monoxide

The huge chunks of limestone in the charge decompose at the high temperature of the furnace, change to calcium oxide or lime, and release carbon dioxide gas according to this equation:

$$CaCO_3 \longrightarrow CaO + CO_2$$

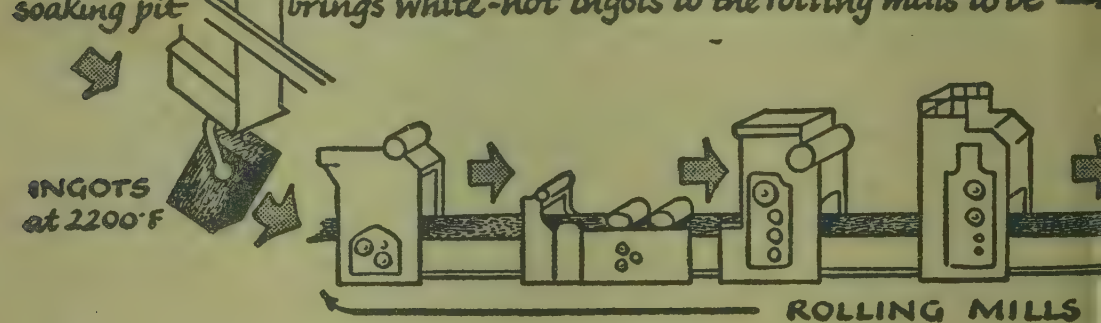
limestone ⟶ lime + carbon dioxide

This lime now goes to work on the phosphorus and other impurities, uniting with them to form a slag which rises to the top of the molten steel and is drawn off. At intervals, samples of the 50 to 550-ton pool of liquid steel are taken and quickly analyzed for carbon content. In about one minute the *quantometer* analyzes the chemical elements in the sample. Light from the glowing steel is broken up and the wavelengths are "read" by electronic tubes and recorded. This makes possible careful control of the final product. Steel, for example, which is to be used for high-speed tools may have a carbon content of about 0.5%, whereas steel that will end up as fence wire may have an entirely different percentage of carbon to give the

best results. The open-hearth process takes about 10 hou compared with only about 10 minutes for the Bessem process.

When the steel is of the right consistency and is rea to be tapped, a jet-tapper is fired at the clay-plugged ta hole in the back of the furnace. The steel flows into a lar brick-lined ladle. Ferromanganese is now added as in t Bessemer process to deoxidize the iron oxide in the ste and to serve as an alloying material. The lighter slag th flows out last and overflows the filled ladle. Between fi and 15 tons of steel are next poured from the ladle in ingot molds, which may be square, round, or rectangula The steel cools and the molds are stripped from the sol steel, then lowered into the nether regions or soaking pi where they are kept at a uniform temperature of 2200° for about an hour.

While some of the ingots are still red hot, they are tran ported to the rolling mills. Here the ingot is moved bac and forth between two heavy grooved rolls, getting a additional squeeze each time until it is a bloom, billet, slab of metal. The product is then treated in other finishin mills. A slab is rolled to the desired thickness of plat sheet, or strip steel. This operation is continuous and un interrupted, and proceeds at the incredible speed of near a mile of sheet every minute. From this ribbon of ste comes the sheet iron for your car, refrigerator, washin



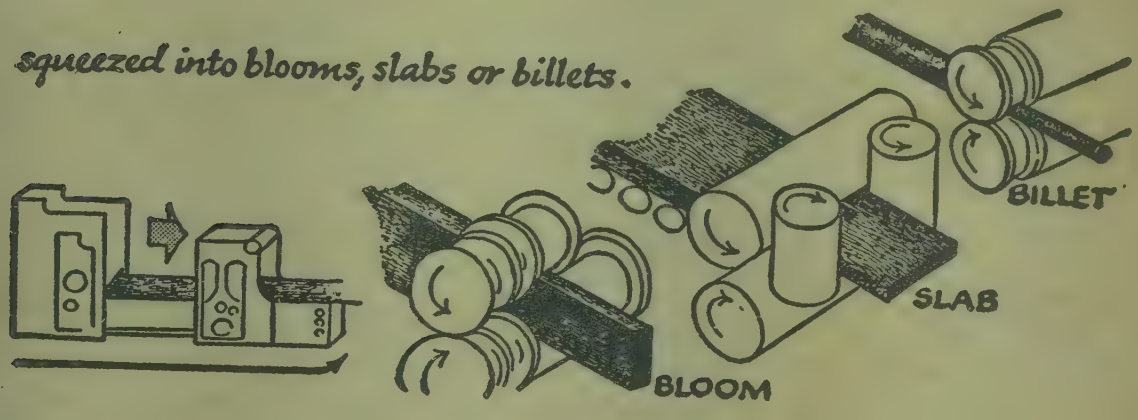
machine, kitchen cabinet, welded pipe, farm machinery roofing, and "tin" cans—which are really steel with a thi coating of tin.

Blooms are sent to another mill where a pair of heav

steel rolls, built like a giant clothes wringer, flattens and shapes them into rails, for example. The rails travel on another roller line to hot saws, where they are usually cut into 33-foot-6½-inch lengths. When cold, each piece contracts into a rail 33 feet long. Other blooms are propelled from one machine to another to emerge finally as structural steel for bridges, ships, machines, and skyscrapers. Billets end up as rods, bars, wire, nails, nuts, bolts, or seamless pipes and tubes for boilers. All of these transformations are controlled from an operating pulpit equipped with dials, push buttons, levers, and "feedback" or self-correcting devices that guide every operation with uncanny precision. Some day—not so far off according to some—the infant automation demon will take over the steel mill without the need for human workers, and specifications and commands will be fed into a single mechanical brain for execution.

New horizons are already visible in the steel industry. Several major innovations are being introduced. First, in an effort to raise steel production with present plants and equipment, air enriched with pure oxygen is being substituted for ordinary air in blast furnaces and steel converters. Supplements of oil or natural gas are also being injected into the combustion zone. Oxygen-enriched air together with these injections hastens the melt in the blast furnace by raising its temperature several hundred de-

squeezed into blooms, slabs or billets.



grees. In the open-hearth and Bessemer furnaces the addition of this so-called "tonnage" oxygen greatly shortens the production time by accelerating the removal of the unwanted carbon. Several large steel plants are al-

ready using this new method in this country. Cheape tonnage oxygen with a purity of 95% supplied by ou chemists is pushing this new development even faste

Second, high-pressure operation in the blast furnac saves time and increases the daily output of pig iron. B means of a carefully worked out system of valves, th pressure inside the sealed blast furnace can be slowly in creased and regulated so that the rate of the blast can b stepped up. This results in a greater output of pig iron an also reduces the consumption of coke by more than 10%

Another new and modest development is the productio of *sponge iron* directly from the ore, using natural gas o petroleum instead of coke and limestone.

Success has also crowned the efforts of one very larg steel company in this country in its long attempt to find a quicker, cheaper and more compact method of convertin molten steel from the furnace directly into semi-finishe steel products. The method announced in 1948 is know as the *continuous casting process*. It eliminates the mos costly and complicated heavy machinery now being use in processing steel. At the present time all finished stee products, from a nail to a bulldozer, begin as ingots from the soaking pits. In the new process, molten steel will be poured from the furnace into a relatively small machine. A chemically inert gas will surround the molten steel to protect it from air-borne contamination. The castin machine will form billets of steel, cool them, and then cut them into any desired length up to 35 feet. It eliminates hammering, pressing, rolling and reheating. "It's like getting cheese directly from a cow," was the way one steel man put it. Not only does it cut costs appreciably, and increase production considerably, but it also makes possible smaller and less costly steel plants. In time, it is thought by some, this new development may help decentralize steel, and allow for even greater expansion of this key industry.

Finally, work is rapidly progressing to meet the ever-increasing threat of a shortage of top-grade iron ore, which generally contains between 60 and 65% iron. The rich iron ore of the Mesabi Range mines of Minnesota, first opened up in 1892, is rapidly being depleted. However, large deposits of low-grade ores are widely distributed

throughout the United States. Iron men are studying and steadily improving methods of mining and concentrating these inferior ores containing as little as 25% iron. *Beneficiation* is the term used for the treatment of an ore to improve it for use in furnaces. A good deal of waste is first removed from the ore by magnetic separation, flotation, washing, and jigging.

Most attention is being given to taconite, an ore which is extremely hard and difficult to mine. The introduction of a new jet piercing machine is solving the mining problem. The jet piercer is a sort of flame thrower which, using kerosene fuel and pure oxygen, delivers a temperature of about 4500° F to drill holes in the tough taconite rock. The rock is blasted apart with steam.

The taconite rock is then crushed, and the iron ore separated from most of the rocky impurities in which it is imbedded. Magnetic separation is part of this process of concentrating the iron ore when it is magnetic, since the rocky impurities are not magnetic. Fine particles of ore cannot profitably be used in a blast furnace because they rise in the current of gases and may be lost. The powder is, therefore, either *sintered* or *pelletized*. In sintering the fine ore is fused with powdered coal into a cake, which is then broken up into pieces. In pelletizing the fine ore is molded with some binder into walnut-sized balls in a special balling mill. The taconite pellets containing about 65% iron are now ready for the blast furnace. Magnetic taconite from the Mesabi mines and other domestic sources is already easing the shortage. In the meantime, too, we are importing increasing tonnage of rich iron ores containing as high as 67% iron from such distant places as the mountains of Venezuela, the Labrador Peninsula, Peru, Chile, Sweden, Liberia, and Brazil. These imports amounted to more than 40 million tons in 1960. The steel appetite of this country, enormous as it is, is still being satisfied.

We are witnessing at this moment a tremendous expansion of the steel industry all over the world. With more people and higher standards of living, the present world steel potential of about 400 million tons may reach 500 million within a few years. Nearly every country will

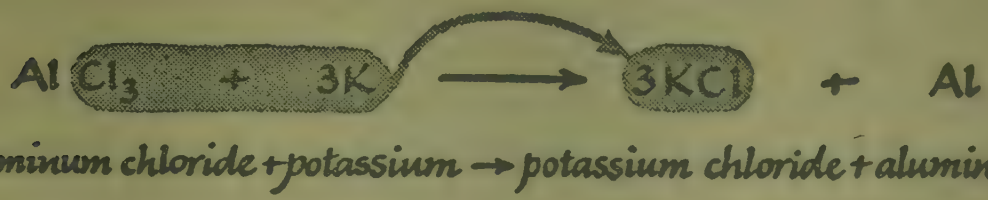
share in this expansion. For example, both India an China, each of whose per capita consumption of steel i only 11 pounds as compared with 1400 pounds for ever American, will be making more and more steel for thei hundreds of millions of people.

Iron has no real rival in terms of tonnage consumed. I stands first and so far ahead of all the other metals that the production of aluminum, its nearest competitor, in spite of its continuous prodigious growth, is only about 1% of steel production. And yet aluminum is more abundant on earth than iron. The crust of the earth to a depth of ten miles is composed of 8% aluminum and 5% iron. Despite the almost universal distribution of aluminum compounds, it was only yesterday in the long history of metallurgy that man learned how to extract this element from its ore at a cost that made its general use worth while.

Both iron and aluminum occur in the earth as oxides. Just as iron oxide (Fe_2O_3) is the main ore of iron, so aluminum oxide (Al_2O_3) is the chief ore of aluminum. This impure aluminum ore is called bauxite and was known to mining engineers for centuries. Yet chemists could not tear aluminum away from its chemical partner, oxygen, as hundreds of years before they had already learned how to separate iron from the same attractive oxygen. Why? The answer is to be found in the fact that aluminum has a stronger attraction for oxygen than does iron. While carbon, the reducing agent used in the metallurgy of iron, can entice the oxygen away from hematite and free the metal iron, carbon is powerless to do the same thing when it is heated with bauxite. Or, put in another way, aluminum is an even stronger reducing agent than is carbon.

The many desirable qualities of the pure element aluminum were known for a long time. Bits of aluminum metal had been obtained from its compounds as far back as 1825 by Woehler, the chemist who had made urea without the use of a kidney. The great Danish scientist, Hans Christian Oersted, who was the first to demonstrate a connection between electricity and magnetism, had also successfully employed the most chemically active metals—sodium and potassium—to force the chemical separation

of aluminum from oxygen. The reaction in both cases may be represented by the equation:



Potassium (K), being more active than aluminum (Al), replaced it from $AlCl_3$.

These early pioneers learned that pure aluminum was very light—only one third as heavy as iron. It was silvery in color, had a beautiful luster, resisted the corrosive action of the atmosphere much better than iron, and could be worked quite easily into any shape or form. It would make an excellent metal for many purposes, it might even turn out to become an ideal substitute for iron. A successful method of obtaining it cheaply would pay off even the most extensive and expensive program of research.

Many minds and hands set to work on the problem. Victory finally came to a young American fresh out of college. It all started when Professor Frank F. Jewett of Oberlin College in Ohio went to study chemistry under Woehler in Germany. Those were the days when Germany was the Mecca of young chemistry students from all over the world. Jewett brought back to America many tales of chemical progress, among them the story of Woehler's successful isolation of pure aluminum for the first time in history. Jewett kept reminding his classes of this elusive element which no one as yet had been able to make cheaply.

One day, as Jewett spoke of the bright future that awaited the man who would develop a method of producing aluminum, one of the students nudged his classmate, Charles Martin Hall. Chemistry had already captivated this young man who was known by his classmates as an ardent amateur experimenter fired by the belief that one day he would make the great discovery. Charles's response to that nudge was, "I am going after that metal," and he went to work at once in his father's woodshed.

One of the most effective ways of separating a chemical

compound into its component elements is to pass an electric current through it. If the electrical energy used is stronger than the chemical attraction of the elements for each other, decomposition results. It is a rather simple process in the case of a compound that is soluble in water. You merely pass a direct current through the solution and the metallic part of the compound collects at the negative pole or cathode, while the rest of the compound collects at the positive pole or anode. Bauxite, however, will not dissolve in water, and therefore presents a different problem. But even this hurdle can be overcome if the compound can be melted at a reasonably low temperature. Like water solutions, molten compounds can conduct an electric current.

Nature is sometimes very stubborn and refuses to cooperate. Bauxite requires a very high temperature to melt, a melting point which makes such a method impracticable. Here was a serious impasse. Perhaps, thought young Hall in a flash of genius, some mineral might be hidden in nature that could dissolve aluminum oxide. After trying many unsuccessfully he came across a milky-white glassy rock from Greenland called cryolite. He melted it with no great difficulty, and tossed in some pieces of bauxite. The molten cryolite was very cooperative; it sucked the bauxite up greedily. Hall was excited. He passed a direct current of electricity through the hot solution, and to his intense joy found bright, metallic aluminum metal deposited on the negative electrode.

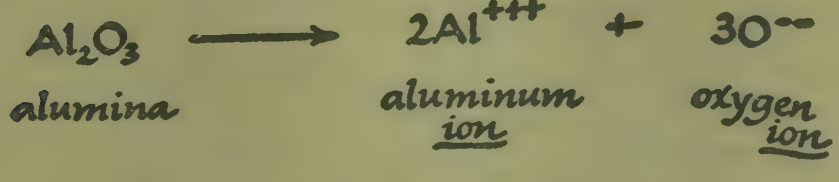
He had at last solved the problem. In 1886, a year after his graduation from college, he burst excitedly into the laboratory of Professor Jewett, and showing him a few aluminum "buttons" in his hand exclaimed, "I've got it." Two years later, aided by the wealthy Mellon family, the Pittsburgh Reduction Company—which later became the Aluminum Company of America—was founded. It is still the largest producer of primary aluminum in the world. Hall died in 1914 at the age of 51, world famous and a multimillionaire. He left most of his fortune to Oberlin College and other educational institutions.

Hall was only 22 years old when he worked out the aluminum process. Exactly two months after he had

handed his teacher the first pieces of pure aluminum he had extracted by his new method, another chemist, Paul Héroult, also only 22 years old, applied for a patent in France for an identical commercial method of aluminum extraction. Independent and simultaneous discoveries are not rare in the history of science. Advances in science are often made in different parts of the world at about the same time. They are frequently the last step in a long series of experiments and analyses of data conducted by many research workers in widely separated laboratories. The scientist who is fortunate enough to publish his discovery first is recognized as the hero of a battle in which many soldiers were engaged.

The heroes of science, on the whole, concede this element of fortune.

Hall's original process is still used, and torrents of molten aluminum have poured from the type of furnace he devised. This electric furnace is an open cell about 30 feet long lined with carbon which functions as the negative electrode. White powdered natural cryolite or the synthetic substitute which has almost completely replaced it is poured into the cell. As an electric current is passed through, it melts. Purified aluminum oxide or alumina, a white powder made by refining bauxite ore, is added to the molten cryolite, and dissolves in it. The aluminum oxide dissociates or breaks up into aluminum ions (atoms carrying a plus charge) and oxygen ions (atoms carrying a negative charge), thus:



Carbon rods or plates of high purity, made from petroleum coke, are suspended in the molten aluminum oxide solution and function as the positive electrode. When the circuit is closed and current is flowing, the positively charged aluminum ions travel to the negative electrode (opposite charges attract each other). Here they change

to molten aluminum metal. This free aluminum settles to the bottom of the cell. At intervals a hole at the bottom of the cell is unplugged, and the molten aluminum is tapped into large ladles, and then poured into molds in which it solidifies as primary pig aluminum. The negative oxygen ions have, in the meantime, traveled to the positive electrode where they have changed to free oxygen atoms. These combine with the carbon atoms of the positive electrode forming carbon dioxide gas which is liberated, thus:

$$C + O_2 \longrightarrow CO_2$$

The process is continuous. Aluminum oxide powder is added from time to time, and the suspended carbon rods or plates are replaced by new ones as they are eaten away, at the rate of 1350 pounds for each ton of aluminum manufactured. Several cells or aluminum pots are joined in series. A "potline" of aluminum is equivalent to a row of open-hearth furnaces in steel making. Each line may contain as many as 150 pots. Each aluminum cell produces between 500 and 2,000 pounds of aluminum every 24 hours.

Domestic bauxite is mined in Arkansas, Alabama, and Colorado. Jamaica, B.W.I., and Surinam in Dutch Guiana also feed our huge aluminum furnaces. Recently the United States Bureau of Mines began experiments at Laramie, Wyoming, to try to get alumina from clay. The Anaconda Aluminum Company, the fourth and latest entrant in the aluminum field, set up a pilot plant to determine the cost of this new process. This step may turn out to be of profound importance.

One hundred years ago the world production of primary aluminum was only a few pounds and it sold for $17 per pound. Today, two million tons of this versatile metal is extracted each year in the United States and Canada alone, and it can be bought for about the same figure in pennies instead of in dollars. At this price it is no wonder that we are turning it out as fast as we can, and building new and bigger plants to meet the fantastic increase in demands for this metal in spite of some inroads by plastics. By 1960

our installed capacity was 2.5 million tons a year—a 15-fold increase in 30 years.

Lightweight aluminum and its alloys, as strong as steel, are the ideal metals out of which to make the curtain walls that clothe the naked steel frames of towering skyscrapers. It is perfect for sending myriads of electric messages and huge surges of electric power through its sinews of wire, for lightening millions of automobiles, trucks, buses, and baby carriages. Aluminum is used in auto engine blocks and in vacuum cleaners, radio and TV sets, cooking utensils, collapsible tubes for paste and shaving creams, and in a thousand and one other gadgets spawned by industry each year. As a reducing agent, aluminum is used to extract other metals such as chromium and manganese from their ores.

Aluminum was the lightest structural metal in use until World War II brought an even lighter metal into the picture. An unprecedented military demand for such an alloy catapulted a tiny infant industry into manhood almost overnight. The production of primary ingot magnesium, the new super-lightweight metal, jumped during the war years from about 3,000 tons to a peak of about 183,000 tons in 1943. In 1961 it stood at about 40,000 tons. Volume for volume, magnesium at 35 cents a pound is less expensive than aluminum.

The newcomer is a soft, silvery metal about 60% as heavy as aluminum, and about one-fourth the weight of steel. In pure form it has little structural strength, but when skillfully alloyed, and using slightly greater thicknesses of the alloy, magnesium can be formed into structural shapes as strong as steel yet weighing only a fraction of what they would weigh in steel. Luggage, portable tools, and much material handling equipment are made with the aid of this metal. Dowmetal is the trade name of a family of magnesium alloys made by Dow Chemical Company, pioneer producer of this metal. Dowmetal A, for example, contains 92% magnesium and 8% aluminum. Dowmetal C, which melts at 1110° F, contains 89% magnesium, 9% aluminum, and 2% zinc. Pure magnesium is used as a reducing agent in extracting the metals chromium and manganese from their ores, and magnesium rods are

used to protect from corrosion the steel hulls of ships, as well as pipes, cables, and steel storage tanks buried in the ground.

Magnesium, which is the sixth most abundant element on earth, is not mined from the solid ground. It is the first metal that led men to the sea for its extraction. Heretofore chemists were content to burrow into the hard earth in search of the metals they needed. The chemist spurned the oceans for the good and simple reason that the stuff he wanted was dissolved in the waters of the sea in extremely dilute amounts. But with magnesium it was different. One element, a nonmetal, had already been successfully extracted from sea water where it occurs to the extent of one part in 15,000. This element is bromine—a reddish, heavy liquid employed in the manufacture of ethyl, the antiknock compound so widely used in gasoline. For almost a quarter of a century millions of gallons of pure bromine have been taken from the sea where it is found as the salt, magnesium bromide ($MgBr_2$).

In the extraction of bromine from sea water one of the by-products formed is another salt, magnesium chloride ($MgCl_2$). This white compound is melted down and then decomposed by an electric current. During electrolysis, pure magnesium metal collects at the cathode, and chlorine escapes at the anode.

Several other magnesium salts are found in the waters of the Gulf of Mexico, where both bromine and magnesium are extracted. The Gulf is an inexhaustible mine of magnesium. Every ton of Gulf water contains about two and a half pounds of the pure metal in the form of salts. These salts are converted into $MgCl_2$ and then decomposed as described above. All primary magnesium metal is made in two plants. One is at Freeport, Texas, and is owned by Dow Chemical Company, and the other, also operated by Dow, is at nearby Velasco and belongs to the government. The deep brine wells of Midland, Michigan, were the birth place of the first commercial magnesium.

The sea is the great reservoir of metals which the rains first washed into the rivers of the globe and then emptied into the oceans. There is hope that some day the chemist will invent and develop ingenious methods of concentrat-

ing the traces of metals found dissolved or suspended in ocean water. Why not? Lowlier forms of life have been doing this for ages. The lumpish lobster, for example, has learned how to concentrate in its tissues the thinly separated copper in the sea, the tuna fish does it with zinc, and the unenlightened algae can do the same with iodine and potassium. The locoweed takes barium from the sea with ease, and the sea squirt can concentrate the metal vanadium at will. Before the rich mines of iron, aluminum, copper, lead, and other metals that keep our industrial world going are exhausted, the modern alchemist may yet find ways of tapping the unplumbed depths of the sea.

It has been estimated that the waters of the oceans contain 7 trillion tons of Bo, 20 billion tons of U, 15 billion tons each of Cu and Mn, and 10 million tons of gold.

Several times the chemist has made valiant efforts to get this gold from the sea. The lure of the yellow metal has always been irresistible. The old alchemists gave their lives to its search. Later, the chemist learned there was gold in the sea in colloidal suspension. Just how much? That was a subject for debate. It varied, of course, with the location of the waters and the depth of the sea. Some said one part per billion, others as high as ten parts per billion. The optimists made some calculations with pencil and paper. At the price of $35 an ounce of gold there was almost a million dollars worth of the metal in a few cubic miles of ocean, they declared. And they calculated, too, that there were 300 million cubic miles of water in all the oceans of the planet. The hills and mountains of the continents were empty cupboards in comparison with this immense storehouse of the sea. Tapping gold from the sea would be more profitable than searching for it in sunken Spanish galleons. There was enough to make every man a millionaire.

In 1920, when Germany needed gold to pay reparations, and also "to spoil the lust of the enemy for gold," Fritz Haber, who had given to his country synthetic ammonia, tried the oceans. His government asked officers of merchant ships to send him samples of sea water taken from the seven seas. He had his own laboratory ship and crossed and recrossed the South Atlantic taking samples.

More than 5000 specimens of ocean water were carefully analyzed for their gold content. Then attempts were made to extract the gold. The concentration of gold, however, was found to be altogether too low, and the project was abandoned. Other serious attempts were made to crack this problem. All proved barren; some were phony. For example, the Electrolytic Marine Salts Company was capitalized in 1897 for $10 million. The company built a plant off the coast of Maine and announced it was ready to extract gold from the Atlantic Ocean. Shipments of gold which had been secretly purchased elsewhere were made to Boston every week. Stocks of the company jumped quickly from 33 to 150. Suddenly, the inventor of the process, Reverend P. F. Jarnegan, disappeared from the country. The operation had been a complete fraud.

A revival of interest in this problem came with the successful extraction of both bromine and magnesium from the sea. Thomas Midgely, the inventor of ethyl and of the freons used in domestic refrigeration, was a man who possessed unusual chemical know-how coupled with the acumen of a hardheaded and successful business man. He predicted in 1934, ten years before he died, that gold would some day be economically extracted from sea water. He pointed out that even though the amount of gold present in sea water is only 1/30,000 that of bromine the price of gold is at least several thousand times that of this liquid element. Also, much more efficient methods could be worked out to get the gold.

Nature has distributed very unevenly many of the metals needed by man without regard to national boundaries or national needs. Many countries lack vitally needed metals and must import them from places outside their own borders. The United States, for example, is either completely or almost completely dependent upon foreign countries for supplies of mercury, chromium, nickel, tin, platinum, tungsten, cobalt, cesium, beryllium, and manganese. Between 80 and 100% of our consumption of these metals is normally imported by us. Thirteen pounds of the metal manganese, for example, are needed for every ton of steel produced. Eleven of these 13 pounds must be

obtained from abroad. Antimony must also be imported to supply at least 40% of our needs.

This unequal geographic distribution has, in times of peace, brought nations closer together in friendly trade. Unfortunately, it has also caused some to embark on imperialistic ventures during which regions rich in various natural resources have been seized and exploited. The absence of strategic minerals, on the other hand, has also had the effect of stimulating the careful conservation of metals, and has spurred chemists to synthesize substitutes such as plastics for these metals. The spectacular rise of the giant synthetic plastic industry in this country is another reminder of the creative power of the chemist.

Shortages of metals have also resulted in greatly expanded research in the extraction of these metals from ores previously untouched because they were too poor in metal content to promise profitable exploitation. In 1890, for example, copper operators in Arizona and Montana could not show a profit with copper ores containing less than 30% pure copper.

Today, thanks to research and new developments, copper ores containing considerably less than 1% of the metal are being profitably worked. The feverish activity with taconite is another illustration of this remarkable change in metallurgy.

During the present century alone the number of metals used commercially has more than tripled. Some of the so-called rare metals are coming into the picture. In reality, many of these rare metals are much more abundant than some of the metals commonly used. For example, zirconium is more than twice as abundant on earth as is copper, and 13 times as plentiful as the familiar metal lead. Yet it is only within the last few years that this silvery metal has been offered for use in any appreciable amounts.

Lighter than steel and almost as strong, matchless in its resistance to many acids, zirconium has found its way into vacuum tubes, surgical wires, and steel alloys used in drills, crankshafts, and ramjet engines. Shredded zirconium is used in some flash bulbs. Enormously expanded research initiated in connection with military demands has been responsible for further stimulus to the production of this

metal. For example, our nuclear energy program turned to zirconium for atomic reactors because of its very low absorption of thermal neutrons. The atomic submarine *Nautilus* contains this vital element, and the atomic future of this new metal looks bright.

The metallurgy of zirconium is very difficult, for the element is highly reactive when hot. At high temperatures it unites furiously with oxygen, nitrogen, sulfur, and carbon, and will even dissolve brick. It becomes brittle and very hard to handle. It is made by the Kroll process developed by the United States Bureau of Mines. Wilhelm J. Kroll, who escaped from Luxembourg before the Nazi invasion, used molten magnesium, later superseded by sodium, to reduce zirconium chloride in an inert atmosphere of argon or helium or in a vacuum. This is the same chemical reaction first used to extract aluminum. About 15,000 tons were manufactured in 1955. At the opening of 1956 the Bureau of Mines stopped producing the metal, and turned over this problem child to private industry for further exploitation. Within two years a private plant was producing sponge zirconium and billets by a continuous process.

Its sister element, titanium, is another of those overshadowed elements that have recently been taken out of hiding. It is the fourth most abundant element and has many desirable properties. When pure, titanium is as stout as steel and only half as heavy. It resists the corrosive action of sea water better than steel, and has a high melting point. Titanium is already beginning to replace steel bolts and engine parts to a limited extent to save weight in aircraft and missiles. It is also being used in food processing equipment, for it prevents impairment of the color, odor and taste of the food. From a virtual laboratory curiosity less than half a century ago, more than 3,200 tons of titanium mill products were delivered in 1961. It may well be that this element, named after the Titans of old and discovered by an English clergyman and amateur chemist in the sand of the beaches of Cornwall, England, will eventually become a valuable addition to the family of structural metals. Like zirconium, it is extracted by the Kroll process, one of the greatest developments in non-

ferrous metallurgy since the introduction of the Hall aluminum process, and the government has dropped its subsidy program and turned it over to private industry. The production of titanium sponge, a porous crystalline form of the metal from which plates, sheets, rods and wire are made, rose from 3 tons in 1948 to 17,250 tons in 1957.

Another new metal virtually unknown a few years ago —germanium—has suddenly jumped into the limelight. It is the active component of the tiny transistors which are rapidly taking the place of the much bulkier and heavier vacuum tubes in radio, TV, and hearing-aid devices. The diminutive post-war substitute for the vacuum tube is no larger than the head of a grasshopper. The need for such light, compact, and sturdy vacuum tubes in all sorts of electronic devices used by the military spurred the development of germanium. The discovery of this element had been predicted by the Russian chemist Dmitri Mendeléeff in 1869. It was described as a dirty gray element with an atomic weight of about 72, a density of about 5.5, and slightly acted upon by acids. Seventeen years later, Clemens Winkler, professor of chemistry at Freiberg School of Mines, stumbled across it in a silver ore known as argyrodite. After the most careful series of tests, Winkler announced the fulfilment of Mendeléeff's prophecy, and named the new element in honor of his fatherland.

Jet engine research resulted in the development of a whole new family of extremely high temperature alloys known as cermets. These are combinations of metals or metallic oxides, and ceramics. Despite all the remarkable advances made, metallurgy still remains a tremendous challenge to man's ingenuity. Fully a third of the known metals still wait for the chemist and metallurgist to contrive methods of extracting them cheaply and in large quantities for the service of mankind.

For example, there is a large group of related metals which have long been known as the rare earths. They are listed in the Table of the Elements from No. 57 through No. 71. Some are actually not rare. Cerium, for example, is more abundant than tin, mercury, and lead. Most of their compounds are found mixed together in monazite

sand. They are all so chemically alike that their commercial separation as inexpensive elements is still a problem for future research. Although they remain out of easy reach there are signs that the rare earths will some day be raring to go, for, as one writer put it recently, "It is not improbable that many of the present well-known metals may, before this century closes, become outmoded in favor of certain more abundant but less-known metals of today." Mixed rare earths (Misch metal) are used in some lighter flints and alloys of aluminum and magnesium. Lanthanum oxide is employed in optical glass, and praseodymium and neodymium in colorants for ceramics and glass.

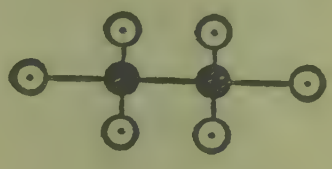
The problem of refining rare metals whose complex metallurgy is still unsolved is not the only challenge left—the manufacture of perfectly "pure" metals is also a goal that has not yet been reached. The metals in general use today are never really pure. Even the so-called *commercially pure* metals contain small but significant amounts of impurities. "Pure" gold, for example, contains as much as 0.4% copper and other substances. Only recently have science and industry begun to explore the preparation of highly purified metals in which the impurities may, in some cases, be less than one part in 100 million. Even a trace of impurity often profoundly affects the behavior of a metal. Tiny crystals of virtually pure iron produced experimentally in the laboratory have been found to be remarkably flexible and to possess a tensile strength of almost a million pounds a square inch—far beyond that of any present alloy or metal used in industry.

If successful methods of producing pure metals in quantity are discovered, it will undoubtedly be possible for metallurgists and chemists to create an entirely new series of metal alloys having strength, heat and corrosion resistance, and other properties much superior to anything now produced. The field of the pure metals represents another great frontier in chemistry to be explored by the chemists of the future, offering another provocative challenge to the young chemistry students of today.

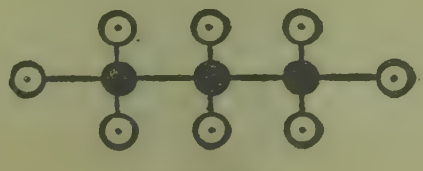
7 Synthetic Gasoline Is Really Here

METALS are tremendously important, of course, but without supplies of fuel for the machines in which they are used, they would serve only limited applications. At the top of any list of fuels stand petroleum and natural gas, but the supplies of both of these fuels will be exhausted before long. Accordingly the services of the creative chemist were put to work in this field. To date the list of accomplishments he has chalked up is very impressive.

You may remember some pages back we mentioned two reasons that account for the enormous number of carbon compounds that are found naturally or made synthetically—isomerism and the substitution of one element for another in a compound. A third factor is the ability of the carbon atom to combine with itself and build up large numbers of new compounds composed of linear or chain molecules. For example, referring back again to methane (page 57), this simplest of hydrocarbons, CH_4, can have one of its hydrogen atoms replaced by a CH_3 group of atoms and change to C_2H_6. This new molecule called ethane can be pictured as



Ethane in turn can surrender one hydrogen atom and latch on to another CH_3 group and form another molecule called propane whose formula is C_3H_8, and which can be pictured as



This chain can be lengthened by means of additional substituted CH_3 groups to form a whole series of hydrocarbons called the *methane or paraffin series.* Hydrocarbons linked together in a straight line are called straight-chain hydrocarbons. Some of the larger and heavier members of this series are octane (C_8H_{18}), hexadecane ($C_{16}H_{34}$) and hexacontane ($C_{60}H_{122}$).

The first four members of this series of hydrocarbons are gases under normal conditions. The next 15 members are all normally liquids, and the rest are solids. Now it happens that ordinary gasoline, the kind that runs your car, is a liquid mixture of several of the liquid hydrocarbons just mentioned. The main members of the paraffin series found in this gasoline are heptane (C_7H_{16}), octane (C_8H_{18}), and nonane (C_9H_{20}). While methane alone accounts for nearly one fourth of the total energy produced in the United States, mixtures of paraffin hydrocarbons power most of the machines and engines that do the world's work. They are among man's most important prime movers.

Petroleum or crude oil is the chief source of these hydrocarbons. Crude oil is generally a dark-colored, unpleasant-smelling liquid found underground either in certain shale rocks or held in huge natural reservoirs under pressure between impervious or nonporous layers of rock. During the boring of salt wells in several sections of the United States some petroleum or "rock oil" was usually found. This oil, for a while, found its way into various medicines and liniments. When, however, the possibility of using this liquid for lighting homes was appreciated, definite attempts were made to obtain it by drilling. Several business men sent a sample of the thick black stuff to a professor of chemistry at Yale University one hundred years ago. The professor, Benjamin Silliman, Jr., made the first systematic analysis of crude oil for them and ended his report thus: "In conclusion, Gentlemen, it appears to me that your Company have in their possession a raw material from which they may manufacture without waste very valuable products . . . by a process which is one of the simplest of all chemical processes." Nothing was done,

however, for there was no particular urgency to exploit his judgment at this time.

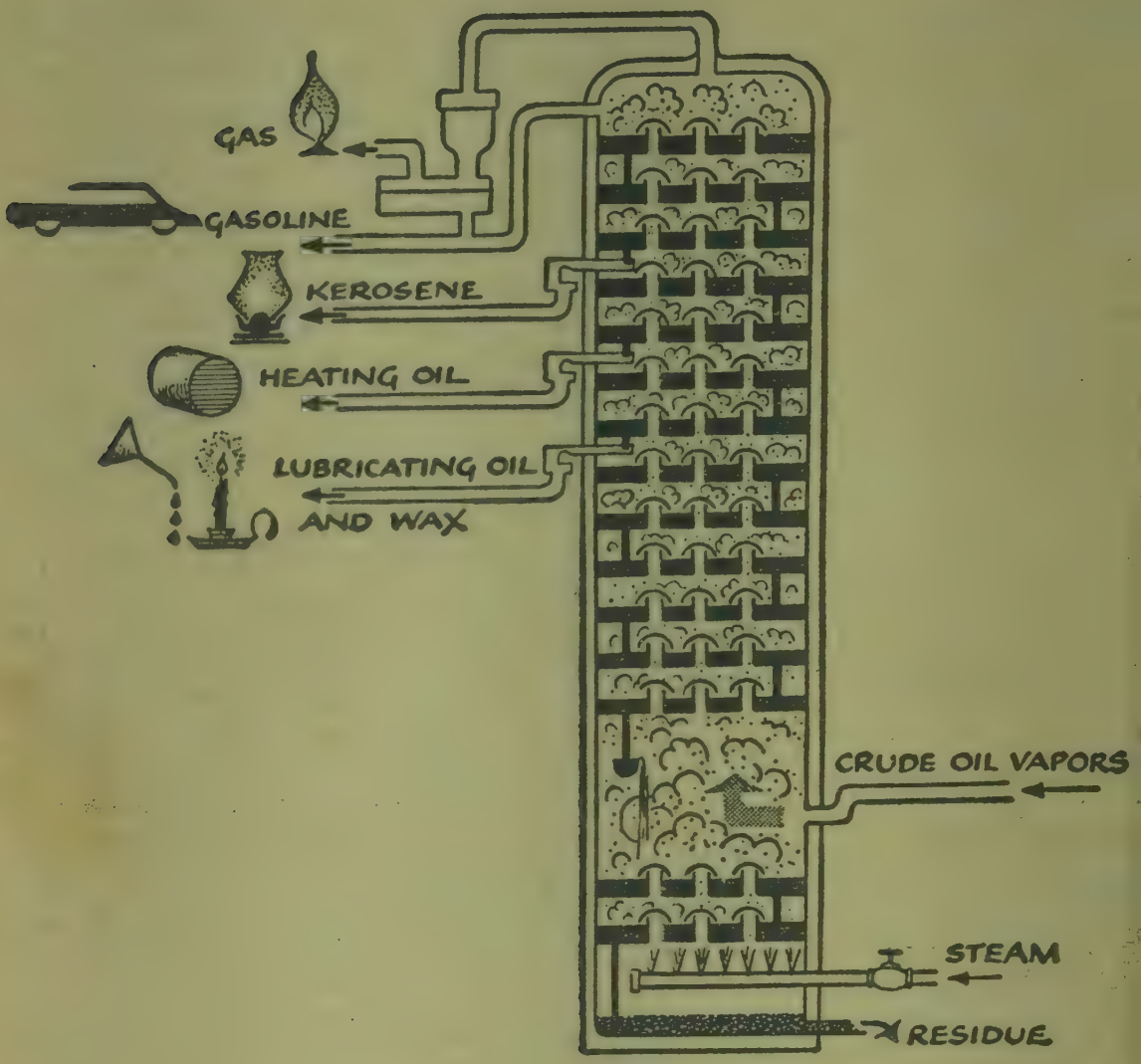
Four years later, Col. Edwin L. Drake was placed in charge of another company which was to attempt to extract oil from the earth in the region around Titusville, Pennsylvania. William A. Smith was hired to dig the well. Late one sultry Saturday afternoon, Smith drew out an iron bit from the well hole he had made and started to measure the depth, which previously had been recorded as 69 feet. Within a few feet of the top there gurgled a black, oily liquid. Using a tin pitcher-pump he managed to extract several barrels of oil. Then with a sample of the liquid in a jug Smith climbed on a mule and set out post-haste to spread the news that "Drake's Folly" was, after all, a dream come true. This dramatic incident ushered in a new era of industry.

After the Civil War, men from the disbanded armies literally rushed to the oil fields, and from then on the oil industry began to grow at an incredible pace until it became the biggest business in the United States. With the increasingly widespread use of automobiles, farm tractors, oil burners, diesel locomotives, and other machinery, the demand for oil and its products grew until today the United States produces each year more than 2.6 billion barrels of oil—that is, about forty percent of the entire world production.

Between the impure crude oil hidden under pressure inside the earth and the final power-packed, high-octane gasoline spans a lot of know-how supplied by our chemists and chemical engineers. Crude oil is a mixture of many hydrocarbons, and varying amounts of many impurities such as free and combined sulfur, wax, and clay. The work of the oil refiner consists first in removing these impurities. Then his major job is to separate this mixture of hydrocarbons into groups of compounds or fractions, each of which may be used for different purposes.

The process of separation, known as fractional distillation, is based upon a simple fact. Each hydrocarbon in this mixture boils at a different temperature. Hexane, for example, boils at 69° C, octane at 125° C, and nonane bubbles away at 150° C. Fractional distillation is like sifting

out a pile of marbles of different sizes. The crude oil i heated in a high cylindrical still furnace. The resultin mixture of liquids and vapors is discharged into a so-calle fractionating or "bubble" tower in which all the vapor



rise. During this action portions of the hydrocarbon mixture are sorted out according to their different boiling points in a continuous, uninterrupted operation. The heavier liquid products, those with higher boiling points, cool off and condense on the lower trays of the "bubble" tower. The lighter fractions, those with lower boiling points, condense on the higher and cooler trays. Several gases—methane, ethane, propane and butane—present in the crude oil are collected near the top of the tower. Below them in descending order a veritable cornucopia of chemical products separates out—naphtha, gasoline, kerosene, domestic heating and diesel oils, gas oils, waxes, paraffin,

tars, and asphalts. The final residue is petroleum coke, a black solid used both for fuel and for making carbon electrodes.

From a 42-gallon barrel of crude oil it is now possible to obtain 19 gallons of gasoline, 16 gallons of gas and fuel oil, two gallons of kerosene, 1.5 gallons of lubricating oils, and 3.5 gallons of other miscellaneous products. In the early days of the petroleum industry kerosene was the most important single distillate of petroleum. Kerosene lamps in countless homes burned millions of gallons of this mixture of hydrocarbons. With the advent of the automobile and the electric light bulb, the picture changed rapidly. The demand shifted from kerosene to gasoline. Numerous processes were, therefore, devised to increase the amount of gasoline that could be obtained from a barrel of oil.

Kerosene, gas oil and fuel oil differ from gasoline in that they are composed of hydrocarbons made up of larger numbers of carbon and hydrogen atoms in their molecules. Kerosene, for example, contains dodecane, whose formula is $C_{12}H_{26}$. By subjecting these heavier fractions of crude oil to carefully regulated higher temperatures and pressures in specially designed stills, these more complex molecules are broken down or *cracked* into lighter molecules such as C_7H_{16} and C_8H_{18}—that is, into the components of gasoline. This general process called *thermal cracking* was first successfully introduced back in 1913 by an American, William M. Burton, a graduate of Western Reserve University.

For almost a quarter of a century thermal cracking was universally used. In 1936 a more efficient process was introduced which gradually displaced it. The new process is known as the fluid "cat cracking" method, *cat* being short for catalyst. One of the catalysts used is a fine, clay-like powder, brought in constant and intimate contact with the oil which has been heated to vapor form. The powdered catalyst flows like a fluid into the incoming stream of vaporized oil so that every molecule of every hydrocarbon bumps into a particle of the catalyst. The bubbling, boiling mass resembles a fine dust storm raging in towering installations, some as high as 20 stories.

Another method of increasing our supply of gasolin is also used. In a sense it may be regarded as the revers of cracking. We start with lighter hydrocarbons which ar cajoled at the right temperature and in the presence of a suitable catalyst into joining up to form the larger mole cules found in gasoline. A larger molecule made up o several units of a smaller molecule is called a polymer and the process of hooking them together like paper clips is called polymerization. Polymer gasoline is made by this method. In 1899 only five gallons of straight-run gasoline could be obtained from a barrel of crude oil by simple fractional distillation. Today almost four times this volume of gasoline is obtained from the same barrel of crude oil. Still another source is the so-called "casing head" gasoline. This is obtained by separating the gasoline vapor present in "wet" natural gas that issues from the well together with the petroleum. This adds about an extra 10% to our gasoline output each year.

In the late 1940's the demand for gasoline reached a critical point in this country. Our needs were outstripping our domestic production. In 1948, for the first time in our history, our domestic production of gasoline and other petroleum products failed to meet the ever-growing demand of our economy. Liquid fuel was being consumed at an alarming rate by mechanized farm machinery, autos, buses, planes, locomotives, oil burners and other heat and power units. More than a million new tractors were purchased that year for farm use. Five million new passenger cars and trucks were added to the more than 30 million on the road at that time. Ninety per cent of all railroad locomotives on order were being built to burn diesel oil instead of the usual coal fuel. Five years later coal dropped below oil for the first time in the United States as our leading source of energy. In that year crude oil supplied 40%, natural gas 22.5%, water 3.1% and coal only 34%. In 1900 it had furnished 89%.

This was the simple statistical picture. Our 1948 daily requirements of petroleum were 5,750,000 barrels. Our domestic production was roughly 5,400,000 barrels a day. This left a daily deficit of about 350,000 barrels that had to be met by importing oil from abroad. This imbalance,

it was predicted, would become even more serious. It was calculated that by 1960 consumption would outrun production by nearly 3 million barrels of crude oil each day, and by 1975 the figure would be closer to 7 million barrels a day!

The chemists, physicists, geologists and engineers of the petroleum industry were not idle. Aware of the ominous trend, they were increasing home production by exploiting new domestic oil bearing areas, controlling the rate of flow of petroleum from new wells, thus preventing loss from gushers, and reaching out for the large oil reserves that lay under the millions of watery square miles of our continental shelves of the Gulf of Mexico and the Pacific Ocean. Oil men were digging deeper and deeper to 22,559 feet—more than four miles—to try to recover large quantities of the oil still left in the ground after conventional pumping by forcing water, gas, or air to the oil-bearing strata. Refiners were wringing millions of barrels of gasoline out of gasoline-wet natural gas, sweating more tens of millions of gallons out of crude oil by ingenious cracking processes, and reducing evaporation losses of gasoline in storage by means of floating-roof tanks, or spheroids under pressure of nitrogen gas. But despite all these heroic efforts, the cold fact remained. We had not caught up with our galloping needs. Furthermore, many believed that all of our estimated petroleum reserves would be completely exhausted in about a quarter of a century.

The United States, realizing the danger, stood on the threshold of another chemical revolution. It envisioned the launching of a major new industry which would free America from its dependence upon foreign sources of oil. Gasoline was to be produced from coal, air, and water on a scale so vast that it would dwarf even the giant synthetic nitrate industry born out of desperation during World War I. Creative chemistry stood ready to save us from becoming a have-not nation in oil.

Developments in synthetic chemistry had been so rapid and broad since the historic day in 1828 when Woehler prepared the first organic chemical from inorganic raw material that chemists felt certain they could convert any grade of coal into high-octane gasoline and other petro-

leum chemicals, at a cost that could easily compete wit the natural products. They could make two barrels o synthetic crude oil out of every ton of bituminous coa and thus insure an adequate domestic supply of petroleur for at least a dozen centuries to come.

Chemists knew that we would need fuel oil for many decades at least, even after nuclear energy had replaced coal and oil as the key sources of our energy requirements. Automobiles, trucks, buses, aircraft, and mobile farm machinery will probably run on gasoline and diesel oil long after nuclear furnaces "burning" uranium, plutonium and thorium will be servicing most of our public utilities and factories. It has been estimated that by the end of the present century 50% of the nation's electrical power will be generated by atomic fuel. Even then gasoline and petroleum products will be working for us in a thousand different ways.

The change of coal into gasoline is based upon a very simple reaction. Gasoline, you remember, is a mixture of several hydrocarbons—that is, compounds containing nothing but carbon and hydrogen. Coal, on the other hand, is a mixture of highly complex molecules of carbon compounds containing a high percentage of the element carbon as hydrocarbons, and only about half as much of the element hydrogen as is found in gasoline. Therefore it would appear that if we could in some way get the calculated amount of additional hydrogen to combine with coal we could convert the latter into gasoline. This process is called coal hydrogenation. A simplified equation for this change may be written:

$$7C + 8H_2 \longrightarrow C_7H_{16}$$

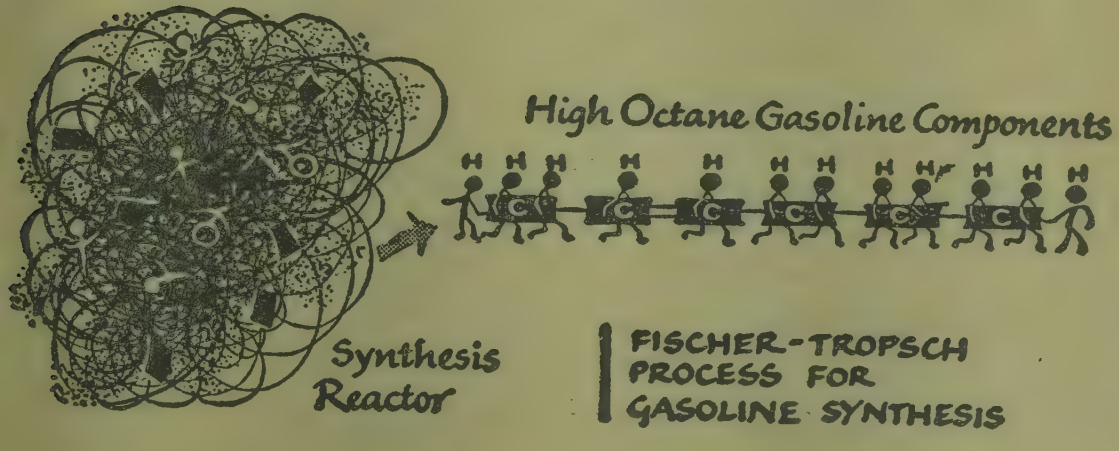
coal + hydrogen ⟶ gasoline

C_7H_{16} is only one of the three main hydrocarbons in gasoline, but the other two, octane and nonane, are also produced at the same time.

About 40 years ago the German chemist Friedrich Bergius announced the method of converting coal into

gasoline by a hydrogenation process which still bears his name. Bergius relied primarily upon high pressures and a suitable catalyst to jolt the complex molecules of coal apart sufficiently to permit atoms of hydrogen to enter, and effect the difficult reaction. During World War I Germany built 18 gigantic plants that turned out 28 million barrels of octane gasoline by the Bergius method, an amount equal to about one fourth of her total gas consumption. After the war, Bergius went to England and explained his method. The British government was interested and built pilot plants to test the process for cost figures. These were found to be too high, and large-scale production was not undertaken until 1933, when a plant was opened by British Prime Minister Ramsay MacDonald at Billingham, designed to manufacture 150,000 tons of petroleum products a year.

At about this time a second method for producing synthetic gasoline was introduced in Germany by Franz Fischer, director of the Kaiser Wilhelm Institute for Coal



Research, and Hans Tropsch. In this new process a strea of pulverized coal is subjected to high heat and pressu in the presence, not of pure hydrogen, but of superheate steam and a jet of oxygen. As a result of this treatment gas called synthesis gas is formed. This gas is a mixture o hydrogen and carbon monoxide, and the equation for th change may be written as:

$$C + H_2O \longrightarrow \underbrace{CO + H_2}$$

coal + steam ⟶ synthesis gas

Synthesis gas can also be made by using natural gas instead of coal, thus:

$$2CH_4 + O_2 \longrightarrow \underbrace{2CO + 4H_2}$$

natural gas + oxygen ⟶ synthesis gas

This synthesis gas is then heated in intimate contact with a powdered catalyst, producing both gasoline and diesel oil. This reaction may be expressed by the following balanced equation:

$$\underbrace{7CO + 15H_2} \xrightarrow{\text{iron catalyst}} C_7H_{16} + 7H_2O$$

synthesis gas — heat — synthetic gasoline

At the very moment that England was opening its synthetic gasoline plant at Billingham, Germany was building gasoline factories and producing 90,000 tons of gasoline per year from coal and lignite, a very inferior type of coal. She needed a million tons of this fuel every year. By means of the Fischer-Tropsch process she was turning out this huge volume for her armies during World War II

when her foreign sources of gasoline were placed beyond her reach.

The United States was aware of this progress in synthetic gasoline manufacture, and for several years chemists of our own Federal Bureau of Mines were trying, on a very modest scale, to develop a better and cheaper method of making gasoline and other petroleum products from coal. This prewar research was stepped up sharply with the passage of the Synthetic Liquid Fuels Act of 1944. In the four years following the enactment of this law, more than $60 million was made available for this work, and more than two hundred scientists of the United States Bureau of Mines were engaged in it. There were several centers for this research such as the Central Experimental Station in Pittsburgh, Pa. Small pilot plants were also operated at nearby Bruceton and also at Morgantown, West Virginia, for the conversion of small amounts of coal into gasoline. Both coal hydrogenation and synthesis gas methods were investigated. The prospects seemed promising.

The federal government then took the next step. Four and one half million dollars were allotted to a private concern for the design and construction of a semicommercial plant that would produce 80 barrels of oil from coal daily. It was to be constructed at Louisiana, Missouri, and the gasoline and diesel oil were to be synthesized by the Fischer-Tropsch process. A larger demonstration plant nearby was to manufacture gasoline and diesel oil by the Bergius method. Both were to supply sound engineering and cost information for a full-scale coal-to-oil plant to be constructed later. On the anniversary of VE Day in 1949 a Burlington Railroad train carrying guests to the dedication rolled the 85 miles from St. Louis to Louisiana, Missouri. Its diesel engines were fired with oil produced from coal in one of these plants. This was a historic occasion.

Our expanding program of research and development was aided by a good deal of data gathered by an Allied Technical Mission that had swiftly followed our advancing armies in Europe to study the synthetic oil industry of Hitler's defeated Germany. This included a careful study of all the synthetic gasoline plants that had survived the fierce bombings of these high priority targets. Several

Germans who had helped develop synthetic oil for th Nazi military machine, including the former chief chemi of the hydrogenation department of I. G. Farbenindustr at Ludwigshafen, were brought over to help build th demonstration plants.

Private industry, too, read the signs and began to pla ahead. Fundamental and technical problems dealing wit the production of artificially made gasoline were tackle in their research laboratories and pilot plants. The Stand ard Oil Company of New Jersey operated such a pilo plant at Bayway, New Jersey, for several years. Anothe pilot plant for converting coal to gasoline and diesel oi by an improved Fischer-Tropsch process was built a Library, Pennsylvania. This project was the joint effort o two large coal and oil interests—Pittsburgh Consolidation Coal Company and the Standard Oil Development Com pany.

Extended research had also demonstrated that synthetic gasoline could be made, too, from natural gas by a modified Fischer-Tropsch method. This manufactured gasoline like that made from coal could also compete in both quality and price with natural gasoline. Carthage Hydrocol, Inc. and the Standard Oil and Gas Company undertook the construction of two full-scale plants, each capable of synthesizing 7,000 barrels of high-octane gasoline and diesel oil daily in the rich natural gas fields near Brownsville, Texas, and Hugoton, Kansas. And although natural gas is the sixth largest industry in the United States with a network of pipelines half a million miles long that reach into almost every region of our country, many realized that natural gas was not the answer. There just is not enough natural gas to last more than 20 years at the rate at which we are consuming it. We are using it not only as fuel but for conversion into alcohols, aldehydes, acids, hydrocarbons and other organic compounds. All our reserves of crude oil, natural gas, oil shale, natural asphalts (gilsonite), and tar sands put together probably constitute only a little more than one per cent of our total available solid mineral fuel. Coal had to be regarded as the keystone of our energy potential for at least the next 15 or 20 years.

That was the situation in 1948. It appeared certain that

private industry would not successfully manufacture synthetic gasoline from coal or natural gas in any appreciable quantities even though the know-how was available. Their engineers insisted that with our present knowledge and current estimated oil and gas reserves, man-made gasoline would cost more per gallon than its refinery equivalent. As a result, some of our leaders in Washington called for federal aid to carry on the essential job. Both the then Secretary of the Interior, Julius A. Krug, and the then Secretary of Defense, James V. Forrestal, urged Congress to subsidize a program that would guarantee a total of two million barrels of synthetic gasoline daily.

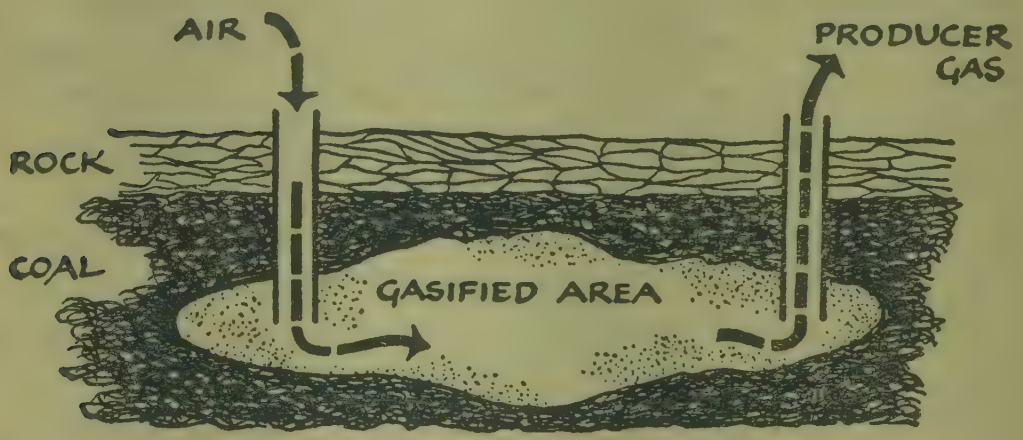
A bill was introduced in Congress which proposed the erection and operation by private companies of three synthetic oil plants each with a capacity of at least 10,000 barrels of oil a day. One was to use the Bergius and the others the Fischer-Tropsch process. The plants would have the Reconstruction Finance Corporation, a government agency, advance money to finance the project for their account.

Eger V. Murphree, then President of the Standard Oil Development Company and one of the men responsible for developing the fluid catalytic cracking process, gave his opinion before a congressional committee. He urged that "the government sponsor the erection and operation by private industry of only one plant which could process coal and be of such size that commercial type of equipment is utilized. . . . That in case private industry is not willing to erect and operate the plants for their own account, then the Reconstruction Finance Corporation be authorized to make contracts with responsible parties for their erection and operation along the same general lines that were followed by the synthetic rubber program. Such operation for the account of the government should be for a limited period and at the end of this period the plants should be sold to the highest bidder." The last sentence of a report to the 80th Congress read, "Establishment of this new industry will decrease our dependence on foreign sources of oil and may thus help remove one of the potential causes of another war."

With such a two-million-barrels a day program going full blast, some saw the coal industry expanding at least

65%, as more coal would be mined to feed these new synthetic gasoline plants. A fabulously new and immense oxygen business would be born to supply the Fischer-Tropsch process which literally lives on oxygen obtained from the air, consuming it at a fantastic rate. A two-million-barrels-a-day gasoline plant would devour 15 billion cubic feet of almost pure, tonnage oxygen every 24 hours. They saw the steel industry expanding rapidly to furnish the more than 16 million tons of steel, about one fourth of our annual production at that time, for the new factories and distribution facilities needed. The underground gasification of coal would also expand to supply additional synthesis gas.

The process of underground gasification was first introduced in the Soviet Union and in England. The celebrated Russian chemist, Dmitri Mendeléeff, who gave us the Periodic Table of the Chemical Elements, was the first to propose it. Instead of mining underground coal in the time-honored way, he proposed to seal off a section of a buried coal seam, set it on fire underground, and



bring the gases produced to the surface through pipes. It proved successful on a limited scale in both Russia and England. Later on, pure oxygen was mixed with the blast of air forced down into the coal mine to produce a gas richer in carbon monoxide.

Under authorization of the Synthetic Fuels Act of 1944 the U.S. government had conducted experiments on underground gasification of coal at Gorgas, Alabama. Here

scientists of the United States Bureau of Mines had sealed off a 300-acre seam of coal averaging 40 inches in thickness provided by the Alabama Power Company, which was a partner in these tests. A fire was started by dropping a thermite incendiary bomb into a bore hole, and air was sent down another bore hole under pressure. From time to time gases were drawn up at the next bore hole and examined. After several years of research our scientists reported that the method used had definite economic possibilities, and that, in fact, it might turn out to be a revolutionary development. By this method we may be able to use vast deposits of coal in mines abandoned either because of the low-grade nature of their contents or the thinness of the coal vein. In addition, this method makes coal exploitation safer and healthier, considerations which are most desirable. Pipeline distribution of the fuel made from underground gasification of coal is still another important advantage.

A new synthetic gasoline industry would also knit together more closely the coal, petroleum, gas, rubber, alcohol, textile, plastics and other large industries. A considerable percentage of our population would shift their places of residence, and our transportation system would need drastic overhauling. There would result, in effect, a more than minor revolution in our whole domestic economy.

More than once before had creative chemistry made us independent of foreign countries for essential raw materials. Synthetic nitrates freed us from Chile, man-made dyes of every hue released us from the iron grip of Germany's chemical dye trust, synthetic nylon made us independent of the silkworm of Japan, artificially compounded rubber rendered us self-sufficient and enabled us to turn our backs on the rubber plantations of Malaya and Indonesia. And now a brand new gasoline-from-coal giant would save us from our dependence on petroleum imports.

What actually happened to this rosy picture? The program never really got under way. First, there was the reluctance of key people in the administration in Washington to undertake any such large scale project on the

principle that the federal government should keep its hands off any area where private industry should operate. It was argued that when the time was ripe, private enterprise would step in voluntarily and take over the coal-to-gasoline project by itself. Leaders in the petroleum industry through the American Petroleum Institute insisted that the methods to be used were altogether too costly to compete with natural gasoline. They hired researchers to prove synthetic gasoline would cost 41 cents a gallon at the gas station. Scientists in the United States Bureau of Mines engaged their own engineering firm and showed we could produce it at a cost of between 11 and 17 cents a gallon at the plant.

As many predicted, the oil interests won the battle. In 1953, the Carthage Hydrocol project which started two years before to make synthetic gasoline out of natural gas in Texas was abandoned after an investment of $50 million. The government's synthetic gasoline program was slowly strangled to death. That same summer its two coal-to-oil plants were shut down as well as the one at Louisiana and placed in permanent standby condition. At the end of that year the gasification of coal experiments at Gorgas were discontinued. Finally, the Liquid Fuels Act which after eleven years expired by law in April 1955 was not extended. The United States Bureau of Mines carried on a very modest research program under its basic legislation, and was left with nothing more substantial than a call for more drastic conservation of our existing supplies of natural petroleum—plus a muffled plea for the manufacture of at least a small amount of gasoline from both coal and oil shale.

Shale is a slate-like rock containing in its pores a substance called kerogen, which upon being heated turns into a thick heavy liquid from which oil products can be refined. There are immense deposits of this rock in Wyoming, Utah, and Colorado—three times as much as the proved oil reserves in crude oil. At Rifle, Colorado, the United States Bureau of Mines' experimental oil shale processing unit had been conducting experiments nearby with this oil shale in the hope that they could deliver gasoline from this source at a cost no higher than that for gasoline de-

rived from petroleum. Not a drop of commercial synthetic gasoline has been made in this country for years.

In the meantime our oil shortage remained very serious, and our imports of oil averaged one million barrels a day from all foreign sources except Venezuela and Canada. To prevent the government from establishing oil import quotas considered essential for the protection of markets for domestic oil and coal, the oil industry regulated its own importation of oil. This action was necessary, too, to avoid upsetting the internal stability of several countries whose economies were closely tied to oil. Venezuela, for instance, would be forced to reduce her imports from the United States if we stopped taking her oil. It would be contrary to the national interest to restrict importation of petroleum from several oil areas of the globe. Thus, in a recent year we imported about 500,000 barrels of oil daily from the Caribbean area, more than a quarter of a million barrels from the Middle East, 50,000 from the Far East, about an equal quantity from our neighbors in Canada, and more than 10,000 barrels from Mexico. Our daily domestic production in 1960 was more than 7 million barrels.

Unless we start making synthetic gasoline from coal or oil shale we will be forced to import even more oil in the years to come, for we are using up our irreplaceable oil reserves at an alarming rate. Many people are becoming more and more concerned over this situation because we are experiencing increasing difficulty in finding new oil sources within our borders. Exploration of new fields is reaching a point of diminishing returns.

No synthetic gasoline is being manufactured in this country for commercial use at the present time. In other countries, however, a relatively small amount of home-made fuel is being turned out. For example, West Germany and Russia are known to be making it. Other parts of the world where natural petroleum and natural gas are either nonexistent or in short supply are turning to the synthetic fuel. The government of South Africa sponsored and financed a project of this kind at Coalbrook, fifty miles south of Johannesburg, and reached the goal of 55 million gallons of synthetic gasoline from low grade coal in 1956.

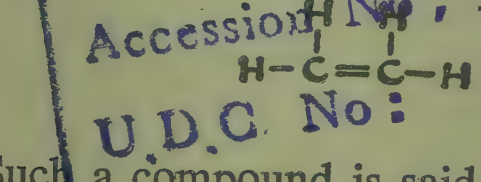
This amount represents about 10% of the country's annua consumption of gasoline. By 1968 SASOL (South Africa Coal, Oil, and Gas Corporation) estimates that it will b selling more than $50 million worth of gasoline and othe chemical products of coal. Mining concerns in Southern Rhodesia in South Central Africa are also exploring the possibility of converting some of their large deposits o bituminous coal into oil by the Fischer-Tropsch process

Another development which resulted in the further draining of our oil resources received its explosive impetus during World War II. This was the conversion of more of our petroleum and especially our natural gas reserves for

other uses. It sparked the recent phenomenal rise of the so-called petrochemical industry. Petrochemistry is the science of converting petroleum and natural gas into hundreds of organic chemicals formerly made from coal tar and other sources. It might also be defined as the science of upgrading low value petroleum hydrocarbons into high value chemicals.

Synthetic ethyl alcohol, the grain alcohol formerly made almost exclusively from sugar by fermentation, is now derived to an increasing extent not from grains currently growing in the sunshine but from crude oil trapped underground for millions of years. Glycerine, previously obtained solely as a by-product during the manufacture of soap from fats and oils, now has its birth in the vapors of petroleum refineries. Acetic acid or vinegar, until recently manufactured by the souring of hard cider, now points with uncertain pride to natural gas for its forebears. Acetylene gas, used in special lamps, and made from the day of its discovery from calcium carbide and water, now traces its ancestry to that same prolific natural gas.

The heating of wood in the absence of air used to be the sole source of wood alcohol or methanol and also of acetone, both excellent solvents. Now they flow in torrents from methane (CH_4), the essence of natural gas. For many years wood alcohol was the main basic material of antifreeze mixtures. Today, 70% of all antifreeze preparations used in our cars consist of ethylene glycol made from ethylene. Ethylene is a flammable, colorless gas, one of the most useful and versatile hydrocarbons, obtained from cracked oil and natural gas. It is used to a limited extent as an anesthetic, and also to make the plastic, polyethylene. Its structural formula is



or C_2H_4. Such a compound is said to be unsaturated because its two carbon atoms are joined not by a single bond as in methane but by a double bond. Atoms of chlorine and other elements, and radicals, such as hydroxyl, can be

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united with such unsaturated compounds forming nu merous valuable, so-called addition products. Among thes products are ethylene dibromide, and ethylene glycol c glycol. The former is one of the components of "Ethyl fluid, an antiknock preparation containing tetraethyl lea (TEL). The ethylene dibromide helps to remove th lead products which escape through the tailpipe. Glyco $C_2H_4(OH)_2$, is a colorless, practically odorless compoun whose boiling point is about 197° C and is used as brak fluid, solvent, and as an antifreeze in radiators under suc names as Prestone and Zerex. Even ordinary hydroge gas, formerly prepared in a variety of ways from severa different inorganic materials, is now a product of th petroleum industry.

There is a host of other useful chemicals, such as ben zene, toluene, xylene and napthalene, formerly obtaine almost exclusively from coal but now derived by the mil lions of pounds from petroleum and natural gas. Mor than one third of all petrochemicals end up in a multitud of plastics and plasticizing agents. Nylon and other syn thetic fibers, synthetic rubber, as well as scores of insecti cides, pesticides, drugs, resins, detergents, refrigerants fertilizers, paints, and explosives all owe their existence t the diversity of chemicals now being forced out of crud oil and natural gas. Stored in gigantic tanks and in man made caverns hundreds of feet below the ground, they await conversion to hundreds of petrochemicals to be shipped around the world.

Thirty years ago less than one tenth of one per cent of our organic chemicals came from petroleum and natural gas. Fifteen years ago this figure jumped to 25%, and today it has mushroomed to an unprecedented 60% and more. Forty billion pounds of such chemicals, valued at more than $5 billion, are now being manufactured each year. Petrochemical plants of huge dimensions and with mazes of pipes and pumps have sprung up mainly in the South with astonishing speed. Here 85% of all petro chemicals are born—75% in the 600-mile crescent from Baton Rouge, Louisiana, to Brownsville, Texas. More than half of the nation's new chemical plants have located in the South during the past few years. The South now

boasts of one third of the nation's chemical industry and is well on its way to raising this to more than 50%, being now the fastest growing industrial region of the country. A tremendous industrial change involving economic and social impacts of deep significance is working in this area of our country.

Strange things are happening among the old established and biggest chemical companies during this petrochemical revolution. The Celanese Corporation of America, engaged in making rayon fiber, went into the oil refining business. They wanted to get an adequate and certain supply of propane and butane which they convert into acetone and acetic acid, two raw materials needed for their synthetic rayon. Esso Standard Oil Company of Baton Rouge, Louisiana, is still very much interested in making gasoline but has turned some of its energies to extracting ethyl or grain alcohol from petroleum. Monsanto Chemical Company is making a new synthetic fiber with the help of huge volumes of natural gas. And du Pont makes a chemical known as cyclohexane from petroleum to feed its nylon manufacturing plants.

Practically all of the benzene, toluene, xylene and naphthalene used in this country was formerly manufactured from bituminous coal by destructive distillation. This is a process of heating a complex organic substance such as coal in an oven or retort from which air has been excluded. It is also known as *high-temperature carbonization*. Instead of burning (since there is no oxygen present), the coal is decomposed by heating, and the vapors liberated are condensed. As the vapors pass through oil-absorption tanks a light oil separates, from which benzene, toluene, xylene and naphthalene are distilled.

Coal gas is also obtained during high-temperature carbonization. From this gas, which is a good fuel, carbon monoxide, hydrogen, methane, ethylene and another hydrocarbon called propylene may be extracted. Other chemicals are also yielded by coal distillation such as ammonia, and a black messy liquid known as coal tar. The total amount of coal tar produced in the United States (120 pounds per ton of coal) depends almost entirely on our steel production because coal gas has been practically

eliminated as a fuel in this country due to the broad and rapid expansion of the use of natural gas. Coal tar is still a very valuable by-product because from it are disentangled many essential chemicals such as anthracene, phenanthrene, pyridine, phenol and pitch.

The most important solid product, the chief reason for the destructive distillation of coal, is coke, a steel-gray, hard, brittle substance consisting almost completely of the element carbon. It is an excellent reducing agent indispensable in the extraction of iron in the steel industry. It is made by heating the coal to more than 2,000° F for 16 hours. The white-hot coke thus formed is pushed out from the oven and quickly quenched in cold water to prevent it from burning up. From every ton of coal so treated about 1400 pounds of coke are obtained.

Coal, the fossilized energy of sunlight, used to be the chemist's sole magic purse of Fortunatus from which he had already learned to draw not only the compounds just listed but also others to make countless drugs, dyes, and perfumes. But this situation changed. Petroleum and natural gas became in recent years what coal was to chemists a generation ago. However, coal was not robbed of all its magic by any means. A new development recently began to take shape involving the treatment of coal not for the specific purpose of making coke or synthetic gasoline but to provide an even greater variety and bulk than before of vitally needed organic chemicals. When the two coal-to-gasoline pilot plants operated by the United States Bureau of Mines were shut down several years ago it was suggested by government officials that the knowledge gained from the coal research carried on there might very well be used to make hundreds of chemicals other than coke or gasoline.

That was a wise suggestion, for the destructive distillation of coal was failing to replenish the unprecedented quantity of organic chemicals being consumed by the new synthetic products introduced during the past 20 years. By-product coke ovens associated with our giant steel industry still turned out more than a billion gallons of coal tar and other by-products each year. But that was not enough. The new development in the treatment of coal supplies even more. The process is called *low-temperature*

carbonization. Instead of heating coal out of contact with air at very high temperatures, as in the manufacture of coke, the coal is subjected to lower temperatures so as to provide less coke, and more of the basic organic chemicals, such as the phenols. This process, for instance, may yield as much as four times the amount of coal tar per ton as does the destructive distillation method.

For many years several companies have been battling the problem of getting more vitally needed chemicals out of coal. The Union Carbide and Carbon Company, for example, built a 300-ton-per-day pilot plant in 1953. Others are experimenting with both Texas lignite and North Dakota lignite. The first commercial power plant to treat bituminous coal for the purpose of getting more coal tar chemicals was announced in 1956. In the heart of the bituminous coal region of West Virginia two large coal plants are also at work on this new chemical front. In the hands of two of the most powerful chemical companies in this country, soft coal near the towns of Institute and Belle is being subjected to lower temperatures, less hydrogenation, and to a jet of oxygen gas and superheated steam for conversion into such final products as xylene, naphthalene and phenols. This is pioneer work and only a beginning. Carbochemistry, as this new science is called, is still very much in its infancy. The pattern of this new enterprise may well follow that of petrochemistry. It surely will have a longer life because our resources of petroleum and natural gas will disappear long before we have begun to exhaust our coal supplies.

The coal industry, sick for a long time from dwindling exports and conversion from coal to oil by the railroads and home heating, welcomed this shot in the arm. It may turn out to be even more important than the steadily rising demand for coal from an ever-expanding electric and utility industry, and from our steel companies which still depend upon coke as completely as they did generations ago to reduce their ore to pig iron.

Coal's real salvation, however, must wait for the day when synthetic gasoline and other oil products will have to be made from the black rock that was once the lush vegetation of the Carboniferous Era.

8 The Rise of Man-Made Rubber

THE synthetic chemist has fought it out with nature on many a different battlefield. Twenty-five years ago he took on rubber. In 1935 the United States consumed 450,000 tons of plantation rubber, more than six pounds for every man, woman, and child in America. In 1945 we used twice this amount of rubber and almost 90% of it came not from nature's plants but from chemical vats. In a single decade a new and gigantic industry had emerged.

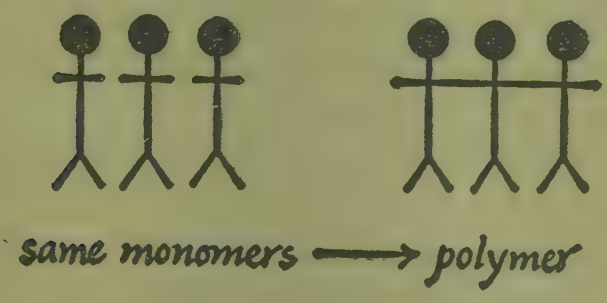
The uncanny skill of the chemist and two simple chemicals—hydrocarbons again—were the key raw materials which formed the basis of this chemical miracle. Butadiene and styrene were the magic compounds. The first, pronounced bū-ta-*di*-een, is a colorless, almost odorless, gas which condenses to a liquid at just below the freezing point of water. Its molecule contains four atoms of carbon and six atoms of hydrogen—that's all. It can be made from natural gas, petroleum, acetylene or grain alcohol. In the process of refining petroleum one of the many chemicals which separates out is the hydrocarbon butane. The molecule of this compound, you may recall, contains the same number of carbon atoms as the butadiene molecule, but it has ten atoms of hydrogen instead of the six found in butadiene. To change butane (C_4H_{10}) into butadiene (C_4H_6) seems simple enough—do a partial dehydrogenation job on it. First, knock off two hydrogen atoms from its molecule and change it to a butylene molecule, C_4H_8. Then rob this butylene molecule of two more atoms of hydrogen. Butadiene results, and the work is finished.

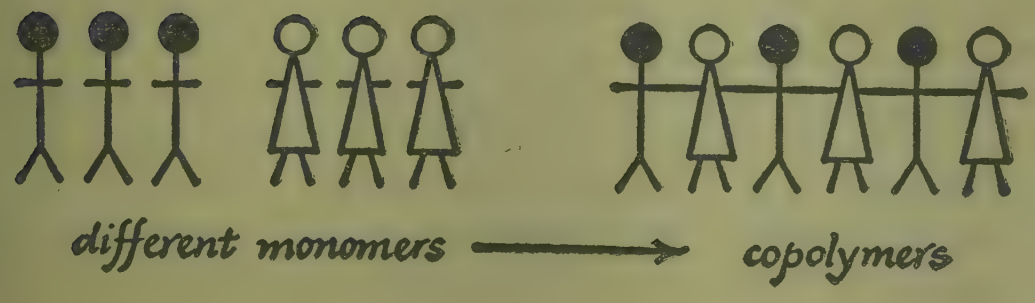
This looks very elementary on paper, but one chemical engineer on the project described this "simple" process thus: "Imagine a huge auditorium with ten million fleas buzzing around in it excitedly. They send you out with a sledge hammer and crowbar and tell you to knock off the right hind leg and the front whisker of each flea and then when you've finished, to sort out all the fleas that you've

maimed in the process." Before the problem was solved, dozens of different catalysts were tried, and scores of difficulties encountered during the "cat cracking" operations had to be overcome. Innumerable details of purification, too, had to be worked out. It was indeed a very hard nut to crack, but it was done.

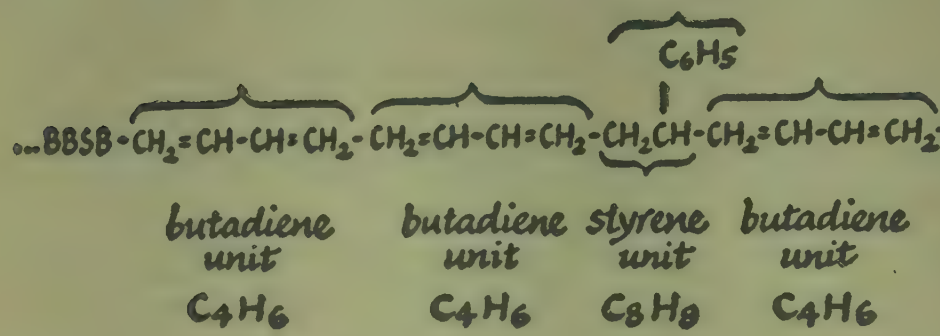
After this minor miracle, three parts of butadiene are mixed with one part of styrene (stī-*reen*). This, too, is a colorless liquid and can be made either from coal tar, benzene or from petroleum. Its molecule contains eight atoms of carbon and eight atoms of hydrogen. The mixture of butadiene molecules and styrene molecules is poured into vats containing soapy water. Here polymerization takes place. Thousands of individual molecules of butadiene and styrene latch on to each other to form long, slender, chainlike molecules.

If the many units of simpler molecules that join together are all alike, the simpler units called monomers form a polymer. Such is the case with polyethylene. This is the plastic used in squeeze-bottles. Polyethylene is made from more than 2000 units of ethylene. If the monomers are different as in the case of butadiene and styrene the product is called a copolymer.





The long-chained copolymer of the synthetic rubber th formed may be written:



where the butadiene (B) molecule (C_4H_6) is written a $CH_2{=}CH{-}CH{=}CH_2$, and the styrene (S) molecul (C_8H_8) is written as $C_6H_5{-}CH{=}CH_2$. The copolyme shown above may be written as $C_{20}H_{26}$ and large number of these joined together make up synthetic rubber. Eac giant rubber molecule may contain as many as 75,00 carbon atoms.

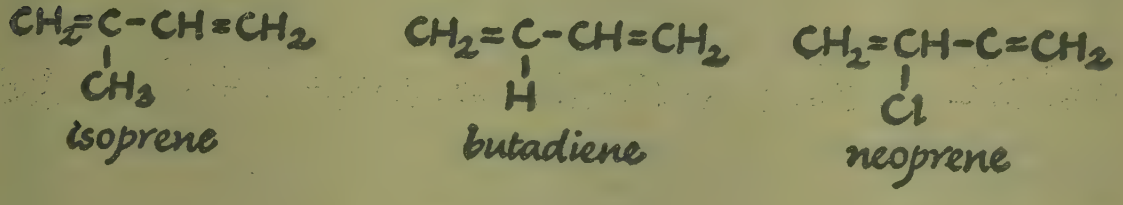
These long butadiene-styrene copolymer filaments be come twisted and kinked, forming coil-like strands that ca be pulled apart or forced close together. When the pull o push is removed, the twisted strands return to their origina size, thus accounting for the elastic and bouncing qualitie of rubber. During vulcanization of rubber (which must b done to make rubber less sticky in hot weather and less hard in cold weather), sulfur atoms are added to the huge ropelike molecules of rubber, cross-linking them and help- ing further to strengthen these coils.

The polymerization of butadiene and styrene forms a synthetic liquid. This new compound is very similar in chemical make-up to, but not identical with, the natural milky latex of the rubber tree. Raw rubber from trees has been known for several hundred years. Lavoisier de- scribed it in his book, *Traité Elémentaire de Chimie* as follows: "Caoutchouc or elastic gum, likewise termed India Rubber, is secured from several plants by incision, and is at first of a thick milky consistency, becoming hard on exposure to air. It is extremely tough, flexible when a little warm, and very highly elastic. Its ultimate elements are C, H, N, and O." Here Lavoisier was in error, for

pure rubber contains only carbon and hydrogen. Priestley, discoverer of oxygen, received a sample of it from a friend who had been to the New World, and reported, "I have seen a substance excellently adapted to the purpose of wiping from paper the marks of a black lead pencil." This was the historic birth of the indispensable eraser, which quickly replaced the bread crumbs previously used for the same purpose.

The purest and best raw rubber is Para rubber, originally collected from trees in the Amazon Valley of South America. Brazil was the world's first great rubber center. Seeds of its Hevea tree were taken from Brazil to England and planted in Kew Gardens. In 1876 selected seedlings from this growth were then transplanted to Borneo, Ceylon, Malaya, Java, and Sumatra, and in the 1920's Brazil finally lost its position to Southeast Asia, which was producing better and cheaper rubber. The largest rubber plantations today are found in Indonesia, Malaya, Ceylon, Thailand, Indochina, and India, where more than 80% of all the world's natural rubber is grown.

Each molecule of natural rubber is also a giant polymer composed of thousands of molecules of a colorless liquid first reported present in rubber by the same Michael Faraday who gave us pure benzene. The pure rubber compound was later named isoprene. Still later it was observed that this liquid changed to a rubberlike solid especially in the presence of pure sodium which acted as a catalyst. Isoprene has the formula C_5H_8, and is closely related to C_4H_6 or butadiene and to neoprene, as their structural formulas indicate:



The synthetic rubber made from butadiene and styrene is not the same as natural rubber; rather one should call it a rubberlike substance, elastomer or elastoplastic. It was named Buna-S, which is derived from Bu(butadiene),

Na(chemical symbol of the Latin name *natrium* for so
dium originally used as a catalyst in the process) and
(styrene). During World War II when American geniu
improved the quality of this rubber, the name was change
to GR-S which stands for government rubber-styrene.

In the single decade between 1935 and 1945 the chem
cal revolution in rubber had been completed. The flow o
natural rubber from the Far East to the United State
stopped and men spoke only of the new rubber whic
came from test tubes. In 1945 during the severe tire short
age in the United States tire salesmen were firing the quip
"No, sir, no tires for your car—rubber doesn't grow o
trees, you know." And the customer almost believed it
A profound chemical revolution had taken place.

Other important advances in rubber chemistry followed
A high percentage of our most widely used synthetic rub
ber began to be made by a newer, faster, lower-tempera
ture process in 1948. An even better all-purpose rubbe
resulted. When used in tires it gave 30% more miles o
tread wear. The $20 million research program which re
sulted in this new development from the old warm (122°
F) process to the new, cold (41° F to subfreezing) method
was directed by the United States Office of Rubber Re
search. Several leading rubber manufacturers and univer
sities took part in this project. Seven years later a new
chemical rubber, most nearly like the tree-grown variety,
finally appeared on the American scene. It is physically
and chemically identical with the best grade of natural
hevea. It is made by polymerizing isoprene itself in the
presence of a catalyst. Its chemical name is cis-1,4-polyiso
prene. It is "natural" rubber and has several trade names
such as Coral and Ameripol SN which stands for Ameri
can-made, polymerization, synthetic, natural. In 1960 it
was in commercial production. The B. F. Goodrich Com
pany and Gulf Oil Corporation have introduced it in truck
tires because, unlike GR-S rubber, excessive heat ac
cumulation does not break it down. That same year
Goodyear Tire and Rubber Company came out with two
new synthetic rubbers—Natsyn and Budene. Other syn
thetic rubbers are du Pont's viton, Shell Isoprene, and
another group of polyurethane rubbers used chiefly as

foam rubbers for upholstery, mattresses, and insulation.

The creation and manufacture of synthetic rubber is a milestone in the history of our country because supplying rubber needs is a basic problem. Our very complex industrial machine literally rolls on rubber. It is animated and cushioned by this chemical product. More than 100 million rubber tires are made in a year. Tens of thousands of tons of rubber are consumed in thousands of other different rubber articles from artificial flowers to welding hose. These add up to more than 1½ million tons—about one-third the rubber produced in the whole world each year.

Our former complete dependence upon foreign sources stimulated the chemical industry to cast about seriously for some nonbiological product that could take the place of crude natural rubber. Synthetic rubber and other rubberlike substitutes gradually appeared, chiefly as the result of the threat of war, the serious fluctuations in the price of natural rubber, and the rising demand for a new type of rubber possessing superior qualities. Finally, when the call for a rubberlike material became insistent enough and the many pressures strong enough, the first commercially successful rubber substitute appeared in the United States.

In 1926 came koroseal, which was used to make shower curtains, rubber sheeting, tank linings, and several other items. In 1929 thiokol was introduced commercially in the manufacture of rubber hose and gaskets. It had first been made five years earlier by J. C. Patrick, a Kansas City chemist, who was trying to make a cheaper antifreeze out of ethylene dichloride and sodium polysulfide. He obtained instead, a gummy mass. Then in 1932, duprene, later named neoprene, was developed by du Pont chemists from a formula first announced by a Catholic priest six years earlier. Father Julius A. Nieuwland was brought here from Belgium by his parents at the age of two and grew up to become a priest and also a professor of organic chemistry at the University of Notre Dame. While working on the problem of new compounds that could be made from acetylene gas (C_2H_2), Father Nieuwland prepared a new compound called monovinyl acetylene.

At the 1925 meeting of the American Chemical Society held at Rochester, New York, Nieuwland read a paper on acetylene compounds as part of a symposium on organic chemistry. Dr. Bolton, director of research at du Pont, was in the audience. He made a patent agreement with Nieuwland and began work on divinyl acetylene which the college professor had also made from acetylene by a catalytic process he had invented. Later, the du Pont chemists found that it was the monovinyl acetylene that could be converted into another substance called chloroprene in the presence of a catalyst. Isoprene and chloroprene are alike except that the CH_3 group in isoprene is replaced by a chlorine atom. More important than this discovery, they observed that this chloroprene polymerized easily to a rubberlike substance which became known as neoprene. This was the first general-purpose man-made rubber prepared in this country. Neoprene turned out to be better than natural rubber in some respects. It resisted the corrosive action of gasoline and of fuel oil, stood up better under continued heat, and was not as easily attacked by several other corrosive agents. It helped seal the fuel lines of our fighting aircraft.

By 1941 a total of only about 8,000 tons of various types of rubberlike substances or elastomers were manufactured in this country. In addition to the three already mentioned, small amounts of other special-purpose rubber were produced here. Standard Oil of New Jersey was making Perbunan (Buna-N) from butadiene and acrylonitrile. This is a self-sealing copolymer elastomer used in the fuel tanks of planes, and also under conditions of low temperature. It did not harden even in Arctic cold. Goodyear had its own rubberlike material called Chemigum. Some Buna rubber was also being made in this country by Firestone. This type of rubber substitute had been developed by German chemists to meet their desperate needs in World War II when a successful blockade by the Allies prevented them from receiving natural rubber from the outside. Being in extremely short supply of petroleum, too, they had to depend upon coal as their raw material for its manufacture. German chemists heated coal and lime together to make calcium carbide which, when

added to water, supplied them with a plentiful amount of acetylene. From this acetylene gas they obtained by a series of chemical transformations the vital butadiene which they polymerized to form Buna.

Patents on this type of rubber were controlled in this country by Standard Oil Company of New Jersey, which in 1929 had made several patent-exchange agreements with I. G. Farbenindustrie, the most powerful chemical company in Germany. As early as 1932 and 1934 four of our leading rubber manufacturers had applied for licenses to make this rubber substitute. I. G. Farben refused to accept certain provisions demanded by the rubber manufacturers. In 1939 Jersey Standard tried to interest rubber fabricators and the United States Government in synthetic rubber. Despite many clear warnings that our national security demanded an American synthetic rubber industry, very little was done about it so that by 1941 our actual production of man-made rubber amounted to less than 2% of our peace-time needs. With the attack on Pearl Harbor and the fall of rubber-producing Singapore, it became apparent that we desperately needed rubber on a scale never before used . . . and that we needed this mountain of synthetics in a great hurry. We had to supply Britain with rubber too, as well as Russia to whom Britain had guaranteed rubber.

How to get it? While drawing on a stockpile of 510,000 tons of natural rubber we had gathered together in two years, we moved rapidly in several directions at once. We ordered the rapid expansion of our domestic facilities that made neoprene and specialty rubbers. We handed out considerable dollars to Brazil, Peru and Venezuela to enable them to increase their small output of rubber. We stepped up our tiny imports of crude rubber from Firestone's rubber plantations of Liberia in Africa. Edison's giant goldenrod project, undertaken during his declining years, was re-examined, and we also took a careful look at a vine of the milkweed family called cryptostegia (krip-to-*stee*-jia). California congressmen saw to it that we subsidized the planting of the wild, bushy, desert shrub guayule (gwa-*yoo*-lee) at Salinas, California. The roots of this plant furnish an excellent rubber product. Our De-

partment of Agriculture distributed and arranged to grow seeds of the rubber-producing dandelionlike Russian kok-sagyz (kok-sa-*geez*) from several pounds of it flown here from the Soviet Union.

But all of these frenzied efforts were not enough. We were getting only a trickle of new rubber when we needed a Niagara. Actually, we could start making synthetic rubber immediately for patents were available in the United States. In March 1942 Senator Harry S. Truman exploded. "Here," he shouted, "is an agreement made with an enemy with whom we are actively at war, and here is our greatest corporation holding patents essential to the war program and it is necessary to use all our legal and legislative power to get the patents into a pool to prosecute the war effort. It is an outrage." Soon after the Justice Department obtained a consent decree which ended the Standard Oil-I. G. Farben antitrust case and freed Buna-S patents from an international cartel with headquarters in Germany. Nine months after we declared war against Japan President Roosevelt then appointed a committee headed by Bernard M. Baruch to make a study of the entire perilous situation. After a thorough survey it recommended that the mainstay of our new rubber program had to be the all-purpose synthetic Buna-S rubber.

In the meantime, a flock of inventors descended upon Washington ready to prove without question that they had better methods for making huge quantities of excellent rubber more quickly and even more cheaply. A refugee Pole, Waclow Szukiewicz, explained to the War Production Board how in 1935 he had made synthetic rubber for his native country out of potato alcohol. He asked for consideration of his process but was ignored. Eugene J. Houdry, an American originator and developer of a catalytic cracking process and head of the Houdry Process Corporation, offered his own method free to the same board, but was turned down. Disappointed though not beaten, this chemist born and educated in France and brought here in 1930 by the Vacuum Oil Company spent $46,000 in July 1942 in ads printed in *The New York Times* and other newspapers and got another hearing. A test was made of his process of producing butadiene, but it was

rejected again because of many problems, including high costs and shortages of critical material needed for setting up his plants.

Others thought butyl rubber was the complete answer. This closely guarded copolymer rubber had been in production on a small scale for several years. It had been developed by two American scientists working for the Standard Oil Company of New Jersey. It was made from two oil refinery gases, isobutylene (97 parts) and isoprene (3 parts). This rubber resisted oxidization very well and could be vulcanized. It was ideal for making the inner tubes of automobile tires. The B. F. Goodrich Company, too, freely offered its know-how for the manufacture of synthetic rubber which they had developed after 16 years. It was known as Ameripol and had already been used in the manufacture of thousands of successful tires—the first ever made in this country of a synthetic rubber.

That wasn't all. Farm leaders started a long and heated argument with oil men over the type of raw material to be used in making Buna-S. Agriculturists and farmers of the grain belt pointed to the vast stockpiles of corn and wheat and, of course, sang the praises of grain alcohol as the raw material. They pointed out that Russia was making synthetic rubber from alcohol. The oil men, on the other hand, were just as articulate and insisted that petroleum was by far the best raw material to use.

The Baruch committee met these conflicting opinions, interests, roadblocks, and other vital problems with good sense and unmistakable firmness. It decided on a definite program. It set as the nation's goal a total of 800,000 tons of artificial rubber a year. Of this amount 700,000 tons were to be Buna-S, 40,000 tons were to be du Pont's neoprene, and 60,000 tons of Standard Oil's newly developed butyl rubber. Of the 700,000 tons of Buna-S, 85% were to be manufactured from petroleum and the remaining 15% from grain alcohol. It was arranged to pool all patents, technical information and manufacturing knowledge on synthetic rubber in the possession of all the six leading rubber manufacturers of the country.

Even before the Baruch report was released, towering stills of oil refineries cast their long shadows over fields

of big-bellied tanks which stored the feedstock of buta diene. Styrene factories sprang into action, and mixin plants and other factories to supply catalysts and othe chemicals accounted for the 51 multimillion-dollar, gov ernment-owned installations stretching from Port Neches Texas, to Ashtabula, Ohio and from El Segundo, Califor nia to Naugatuck, Connecticut.

Before very long production of all types of man-made rubber ran well ahead of schedule. In 1946 we turned ou more than 760,000 tons of synthetic rubber and used an additional 240,000 tons of natural rubber. This astound- ing figure of more than one million tons was as much rub- ber as was used by the entire world in any single previous year. This rubber project had cost the American taxpayer about three quarters of a billion dollars. It was next in magnitude only to our $2 billion investment in the highly secret atom bomb project, in the costly air search which had been going full blast, and in the development and production of the proximity fuse used in shells and guided missiles which amounted to $800 million.

The war years had proved that we could produce all the man-made rubber we needed and that we could be inde- pendent of the rubber of Southeast Asia. Leaders in gov- ernment and business soon raised the question as to whether the government should turn over its rubber plants to private industry for free competition with world natural rubber, or whether it should stay in this business or pass appropriate legislation to protect this new industry in the hands of private capital until the threat of plantation rub- ber had passed.

Some recalled the tragic fate of the indigo industry back in the early years of the present century. At the beginning of 1900 there was a thriving natural indigo industry in India which supplied the world with this natural blue dye. Almost two million acres of land were under cultivation, yielding 17 million pounds of the dye valued at $20 mil- lion. Thousands of natives were engaged in the operations. In 1882 the chemical structure of this dye was determined by Adolf von Baeyer and a few years later indigo was synthesized. Then within ten years the process of manu- facturing it from raw materials was developed to such a

point that it could be made at a price which was even lower than that of natural indigo. The struggle between natural indigo and synthetic indigo was short and furious. In 1927 the United States was manufacturing synthetic indigo, the same chemical indigo it had imported for years from the fields of Asia, at the low cost of 13 cents a pound. The death knell of the indigo industry was sounded when the first batch of synthetic indigo was turned out in the flask of a chemical laboratory. Indian indigo died almost overnight, leaving behind a trail of profound economic problems for the people of India.

Would higher costs, inferior quality, or inadequate reserves of raw material needed for synthetic rubber tip the scales in favor of supporting foreign plantations of rubber? Four years of government-controlled rubber manufacturing seemed to answer in favor of man-made stuff. In 1946 we were making GR-S rubber at an average cost of about 14¢ a pound. The government-established selling price of this type of rubber was 18½¢ a pound as compared with the 1941 market price of 22½¢ for natural rubber in Singapore. Furthermore, experts agreed that our GR-S rubber was at least as good an all-purpose rubber as the best natural rubber. Our domestic factory product of automobile tires gave greater mileage than the pre-war automobile tire tread. For the sidewalls and carcasses of tires, however, it was still necessary to blend some natural rubber with the synthetic because GR-S did not stand up well under heat. For trucks, airplanes and buses a considerable amount of natural rubber was mixed with GR-S to give a satisfactory tire.

Finally, it was unanimously conceded that the two main raw materials needed for our synthetic rubber, butadiene and styrene, could be supplied in sufficient amounts since they could be manufactured from both coal and grain alcohol even when our reservoirs of natural petroleum ran dry. Our coal reserves, it was agreed, would last at least another 2400 years, and ethyl or grain alcohol can be made cheaply from the starch of corn, potatoes or practically any agricultural product, giving us an unlimited and replaceable raw material for synthetic rubber.

Our government rubber policy had, in part, been influ-

enced by all of these considerations. The most compellin factor, however, was declared to be our national securit in the face of an unsettled international situation. Follow ing prolonged and heated hearings on rubber, conducte by Representative Paul W. Shafer of Michigan before subcommittee on Armed Services, the Rubber Act o 1948 became the law of the land. "It is the policy of th United States," the act read, "that there shall be main ained at all times in the interest of national security an common defense, in addition to stockpiles of natural rub ber, a technologically advanced and rapidly expandable rubber producing industry to assure adequate supplies o synthetic rubber to meet the essential civilian, military, and naval needs of the country." To implement this policy, the President of the United States ordered the maintenance in an operating or stand-by condition of rubber facilities with a rated production capacity of not less than 600,000 tons of Buna-S a year, and not less than 65,000 tons a year of special-purpose synthetic rubber.

This policy was pursued for six years. The government, through the large rubber manufacturers who operated our plants, turned out increasing tonnages of rubber each year. In 1955 we made almost one million long tons of synthetic rubber, of which 90,000 tons were exported. That same year we also used about 600,000 tons of natural rubber and 280,000 tons of reclaimed rubber—indeed a very impressive record of success. The ratio of natural rubber used by us to the synthetic rubber kept declining each year. Now the Rubber Act of 1948 provided that the government get out of the rubber business and turn it over to private enterprise as soon as security interests warranted such action. In line with this policy and in accordance with the various provisions of the Rubber Facilities Disposal Act, all of the 27 government-owned synthetic rubber and rubber ingredients factories were offered for sale to private industry. The final filing date was May 27, 1954, and sealed bids were opened soon thereafter.

Within less than a year the government's second largest industrial monopoly began breaking up, and by 1956 the government was out of the synthetic rubber business. All controls on rubber manufacture were lifted, and unre-

ricted competition between natural and synthetic rubber revailed. Even federal grants for rubber research and evelopment came to an end. The government had re-eived $425 million from the sale, and while some insisted iat the American people had made a profit of $10 million n the transaction, others were equally positive that this vas just another giveaway by the administration.

Ten years of government ownership of the huge rub-ber business of the country had proved a success. Not only iad it met the wartime emergency needs of America, but t also produced a better product and a cheaper commodity han prewar natural rubber supplied by private business. The Federal Facilities Corporation reported to Congress hat the last year of government operation accounted for production of more than 850,000 long tons of GR-S rub-ber, and about 80,000 tons of specialty rubbers including 55,000 long tons of butyl. This last figure represented a drop due to the introduction of tubeless tires as standard equipment on practically all new passenger cars. The price of its workhorse of synthetic rubber, GR-S, kept stable at about 23 cents a pound, while in the same period natural rubber prices ranged erratically from 20½ cents to as high as 52 cents a pound, due to speculation, unsettled political situations, and a growing world demand for more rubber. The government's operation was unusually profitable, showing an income amounting to close to 20% of total sales that year.

With such an impressive record behind it, the govern-ment offered some advice to private industry as it began to take over the whole rubber business again: the new owners would have to step up synthetic rubber output to meet the world's growing demand.

In 1935 total world rubber production was 870,000 tons; now it had reached 2.9 million. In 1961 this figure had risen to about 4 million. Experts estimated that by 1965 world needs would climb to the astounding figure of almost 5 million long tons. While world consumption would be increasing at the rate of more than 4% per year, natural rubber production was increasing at less than one per cent each year. Hence the need for more synthetic rubber.

The government's advice was taken very seriously. began expanding our existing plants in Kentucky, Lou ana, Ohio, and Texas. The General Tire and Rub Company planned the first post-war, privately finan and completely new and integrated rubber plant at Odes Texas. Firestone, world's largest rubber producer, plan a multimillion dollar expansion to increase its synthe rubber capacity 50%. In 1960 we made 1.5 million tons synthetic rubber.

The rubber problem is an international one, and a co plicated one. Only the United States, Canada, and p haps West Germany, Italy, Japan, and the Soviet Uni are producing synthetic rubber in quantities that cou make these countries self-sufficient if need be. The sy thetic rubber capacity in 1961 of non-Communist Euro and Asia was estimated to be about 750,000 long ton The USSR together with the other Communist countri probably had a synthetic rubber capacity of slightly mo than this amount. The rest of the world still depends natural rubber. In spite of the fact that synthetic rubb costs less to produce than tree rubber, they must impo the natural brand because of dollar shortages, as well for political reasons. We, too, are importing large quan tities—as much, in fact, as we did before World War —to blend with the synthetic product used in bus, truc and airplane tires. A minimum ratio of 40% natural t 60% synthetic is used. Additional quantities of natura rubber are being brought here for stockpiling.

Some maintain that we continue to import large stock of crude rubber in order to bolster the economies of othe nations whose friendship we need in this era of inter national tensions. R. D. Young, President of the Rubbe Trade Association of New York, testified before a congres sional committee late in 1947 as follows: "The Congres is today considering a program involving the expenditur of large amounts of money in European countries. Ou country is embarking on a program involving the reha bilitation of the economies of other countries (through ai from the United States) in order to preclude condition which might imperil the welfare of the people not only o other countries but also of the United States. This is na

onal security in the broadest sense. It must be obvious at every pound of synthetic rubber used in this country presents a loss of dollar exchange to the natural-rubber roducers in the Far East. . . . If there be taken from the atives a substantial proportion of the dollars which they ould receive for their production, neither stable econo-ies nor political conditions can be created. The entire conomies of Malaya, the Netherlands East Indies (In-onesia), and other Far Eastern countries depend to a ery large extent on natural rubber. If maximum quan-ties are not absorbed in international trade, seeds of un-est will be planted in these areas with resulting impact pon our own national security."

On the other hand, Walter J. Murphy commented edi-orially in the February, 1948 issue of *Industrial and Engi-eering Chemistry*: "If the basic idea of the Marshall Plan s to pour dollar exchange into the hands of foreign Gov-rnments, then we should buy huge quantities of crude itrate, subsidize the natural silk growers of Japan, and evive natural indigo cultivation in India. Is it the thought f the State Department that we should halt scientific and echnological advance because they may disturb the pres-nt economy of one or more foreign nations? Would it not e wiser to let nature take its course? Very likely the pop-lations of Malaya and Indonesia would be far better off ventually if those extensive areas now devoted to rubber rees were utilized in a program of wide agricultural di-ersity." But our stockpiling of natural rubber did not stop.

In the meantime, the blow dealt the natural rubber in-lustry in the Far East during World War II was only emporary. In 1958 Indonesia produced 750,000 long tons f rubber and Malaya 650,000 long tons. Even though ree-grown rubber remained the world's chief rubber re-ource, supplying 2 million tons—one-half of the world's ew rubber requirements—it still faced a fierce competitor. Test-tube rubber could very well destroy it. Only a more erfect rubber tree could hope to compete successfully ith synthetic rubber. Said one government expert, "In a ompetitive race between natural and synthetic rubber, ased on price alone, the impact on the price of natural ubber of doubled or tripled yields per acre of rubber can-

not be ignored." This seemed to be its only hope in t long run.

In 1955 the Malayan rubber industry set up a new search institute and experiment farm to increase the yi and improve the quality of its rubber trees. From 1930 1940 its average annual rubber production was arou 300 pounds per acre. It is hoping eventually to increase t yield from the present average 400 pounds of rubber p acre to as high as 1200 pounds or even more. Modern se stock used for replanting can produce rubber, some b lieve, at half the cost of handling the older low-yield tree In the meantime, in spite of the growing world dema for rubber, experts in the field expect at best no more tha a slight increase in natural rubber during the next ten more years. Synthetic rubber will have to take care world rubber demands more and more.

While the United States has solved its rubber suppl problem, Great Britain, too, has taken steps in that direc tion. In addition to increasing its rubber plantations i Malaya, it started expanding new rubber plantations i Nigeria in Africa. It has also begun to manufacture it own synthetic rubber of the GR-S type. Its domestic o refineries are furnishing the necessary butadiene and sty rene, and they reached a production figure of about 75 000 tons of synthetic rubber in 1960. This has helped fre England from American GR-S which they need fo the improvement of their automobile tires, and has also helped reduce their dollar expenditures.

Canada now produces about 100,000 tons of syntheti rubber, and East Germany somewhat less. Other countrie have followed this course owing to the pressure of th need for better quality and cheaper rubber. West Europ in 1961 consumed about 300,000 tons of imported syn thetic rubber, in addition to about twice this amount o their own manufactured synthetic rubber. These oversea synthetic rubber facilities are owned jointly or completely by American rubber concerns. North Ireland, for example has a 20,000-ton-a-year neoprene plant, built by du Pon in 1961. Le Havre, France, has a 10,000-ton-a-year plant constructed by Firestone that same year; and Goodrich is joint owner of a 6,000-ton-a-year plant in the Netherlands

Perhaps natural rubber some day will all but succumb
o the man-made product. Creative chemistry, some be-
eve, will one day drive the manufacturers of plantation
ubber out of business, even as synthetic indigo destroyed
ne natural indigo industry in India. It has been pointed
ut that the spread of free and independent governments
n Indonesia and other rubber-producing areas will bring
n end to cheap labor. Other significant changes in their
conomies and standards of living will follow. Rubber
rees will make way for more profitable timber and more
liversified food crops. This change will, of course, be
radual. There will be time enough, it is believed, to per-
nit a transition free from the widespread hardships and
njustices of sudden dislocations.

Today we can turn our backs on the rubber trees grow-
ng in jungles halfway around the globe and enjoy a bet-
er product from our test tubes. Tomorrow there will be
more wonders. Synthetic chemistry is still vigorous, crea-
tive, ingenious, and full of promise—not only for the mil-
lions living within our own borders, but also in the long
run for the tens of millions of toiling, restive natives of
Asia and Africa.

9 The Race for Newer Synthetic Fiber

In China for more than forty centuries there flourished a ashy white moth about half an inch in length, which i its caterpillar stage spends all of its waking life feedin voraciously on the leaves of the mulberry tree. Then fro its spinning glands it squeezes out through a tiny hole lo cated near its lip a thick liquid, a drop of which it attache to some stationary object. It then draws this liquid into thread as it turns solid. With this thin, cylindrical threa the tiny creature, by instinct as old as time, spins a co coon in which it is soon enclosed and protected until th day when it emerges as a moth.

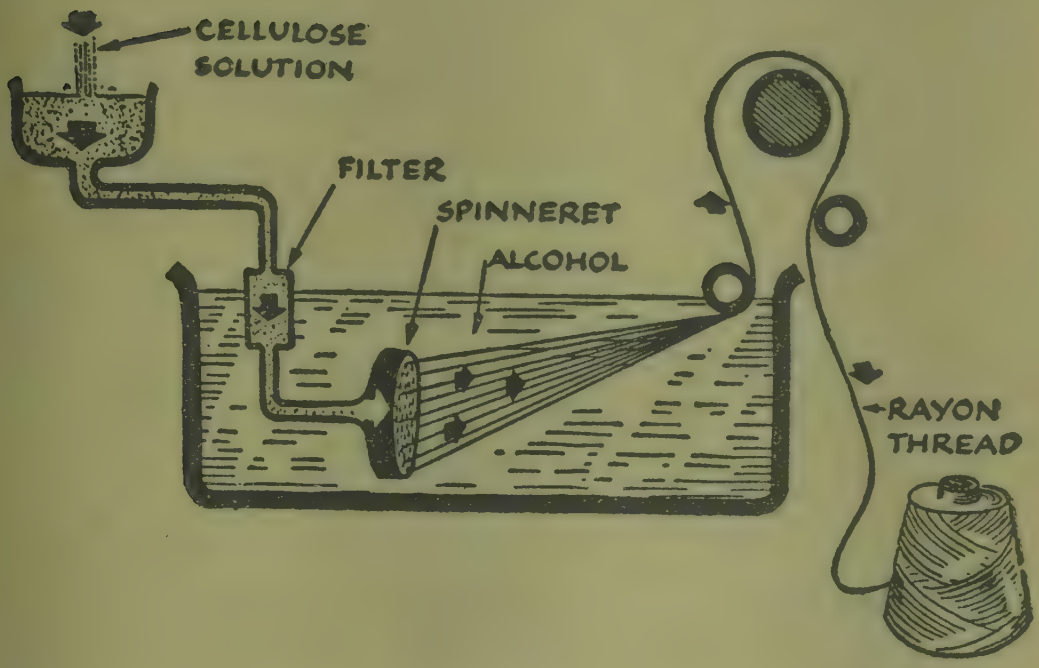
Some bright and enterprising Chinese got the notion that this thin thread could be used to make cloth. So, tak ing a cocoon before the moth could poke its head out, he killed the insect by careful heating and unreeled half a mile of the silky filament. Then he tried twisting a few of the filaments into yarn. No doubt he failed many times, but one day he succeeded in making silk threads for weav ing. Thus was born the natural silk fiber and the sericul ture industry.

The making of silk fiber was a zealously guarded secret for generations, but its knowledge eventually reached Japan and later France and Italy. By improved methods both the quality and the yield of the silk became better. By 1940 the world produced 85 million pounds of it, with Japan accounting for 70% and China 20% of the total. Silk fabric was the textile par excellence and was firmly entrenched.

Many men must have looked with envious and jaun diced eyes on this "insect" industry. They must have had the same thoughts as did Robert Boyle, the great Irish scientist who wrote in his "Micrographia": "There may be a way found out to make an artificial glutinous com position, much resembling if not fully as good, nay better, than that Excrement, or whatever other substance it may

be made of which the Silkworm wiredraws his clew." This was recorded in 1664. Many years later, the celebrated French naturalist and versatile scientist, René A. F. de Réaumur, had watched the spider at work and, marveling at the web it had spun, expressed the same thought. Two hundred and twenty years were to go by before Boyle's hope came true.

In 1884 Joseph W. Swan, an Englishman, looking for a suitable filament for an incandescent electric light, took



some guncotton or nitrocellulose dissolved in vinegar and squirted it through tiny holes into a tank of alcohol. From this unusual combination of chemicals came a long thin filament. But instead of a lamp filament he was in possession of a new artificial fiber. It was made into threads and then woven into cloth and exhibited under the name of "artificial silk," for indeed it had the luster and feel of natural silk. Swan was no businessman. He failed to improve and exploit his invention.

At almost the same moment, across the Channel a young Frenchman who, as a student of the immortal Louis Pasteur, was investigating a disease which had very seriously attacked the silkworm in France, hit upon the same idea as Swan. He took out a patent for the manufacture of his brand of artificial silk, and soon afterward the first

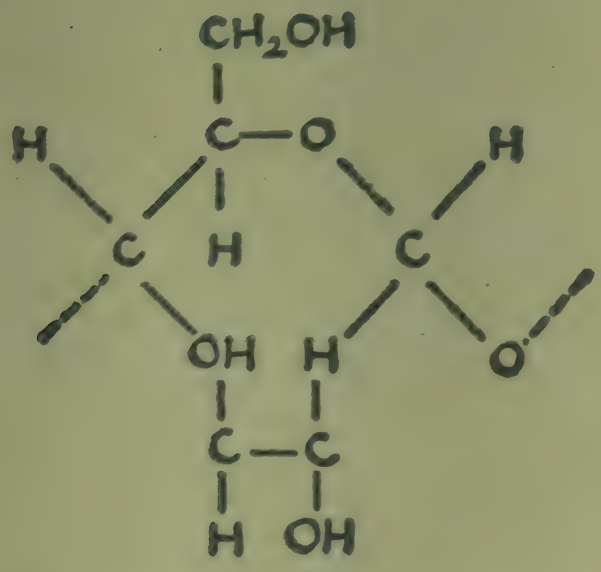
gown ever fashioned from an artificial silk was displa at a Paris Exposition. It created quite a hubbub. Co Louis Marie Hilaire de Chardonnet, physiologist and ventor, became an industrialist. He opened a factory in native town of Besançon and in 1901 started making improved version of his original artificial silk cloth to me the needs of the women of France. This marked the bir of the man-made textile industry, which started slowly b soon grew phenomenally. In a recent year 4.5 billi pounds of man-made fibers were manufactured in 30 di ferent countries, while the amount of natural silk produce that year was only one per cent of this immense figur The United States leads the world in this new billio dollar industry.

Cellulose fiber products are now known as rayons. A rayons are made from the same raw material, cellulos This substance is the most abundant chemical compoun found in the woody tissues of all plants. There is more cel lulose used throughout the world than any other basi commodity except water. Cotton fiber is almost pure cel lulose. Linen, hemp, jute, ramie, wood pulp and pape contain large percentages of cellulose as their main ingredi ent. Pure cellulose belongs to a class of organic compound called carbohydrates which are made up of three element —carbon, hydrogen, and oxygen. The hydrogen and oxy gen are always present in the same ratio as they exist i water—two atoms of hydrogen to one of oxygen.

Like rubber, cellulose is a high polymer. It is made up of perhaps three thousand units of the group $C_6H_{10}O_5$. Starch is composed of the same group; it, too, is a high polymer. Since we are not certain of the exact number of these groups that make up the molecules of either cellu lose or starch we designate their simplest formulas as $(C_6H_{10}O_5)_x$ and $(C_6H_{10}O_5)_y$ respectively, where x and y are unknown. Glucose, the sugar found in corn syrup, is another carbohydrate. Its formula is $C_6H_{12}O_6$.

The cellulose molecule is formed in plants by the link age of the small molecular units in extended chains. The smaller unit consists of a molecule of glucose from which one oxygen atom and two hydrogen atoms have been re moved. The cellulose chain molecule may be represented

as made up of $C_6H_{10}O_5$ units whose structural formula is:



The artificial silk of Chardonnet is made today by several methods not originally employed by the French inventor. More rayon is now made by the viscose process than by any other, because of the lower cost of the raw material and the superior quality of viscose rayon. The raw material is cellulose obtained from spruce, pine, or other trees, or from linters—the short cotton fibers left on the cottonseed after separation from the cotton plant. A cotton fiber consists of only one cell, varying in length from ⅜ inch to 2 inches attached to the seed of the cotton plant. Under a microscope a cotton fiber appears as a flat thread resembling an empty, twisted fire hose.

Cellulose does not dissolve in water, of course, or your paper napkin would disappear when wet. It can be made soluble, however, when steeped first in lye solution, and then treated with a colorless, highly inflammable liquid called carbon disulfide (CS_2). After some further treatment the cellulose dissolves, forming an orange-colored solution which turns into an amber-colored, jellylike syrup called viscose. This substance is the equivalent of the sticky fluid forced out of the silk moth's orifice, which on exposure to air hardens into a thread. Viscose will not naturally harden in air, but can be made to do so if forced into some liquid in which it will not dissolve.

The viscose syrup from the chemical tanks is now

squeezed under pressure through a number of tiny holes in a small metal cup, about the size of a dime, called a spinneret. From this spinneret (named, naturally, after the organ through which the silk worm ejects its own filament of silk) the viscose enters a tank or bath filled with a solution of two chemicals, sulfuric acid (the acid found in your car battery) and a salt, sodium sulfate. The viscose changes at once from a thick fluid to a solid thin filament flowing endlessly through each of the tiny holes in the spinneret. Several of these filaments are then twisted into a thread by means of a revolving spindle. The threads are treated to remove any excess chemicals adhering to them, dried, and wound on spools or in skeins.

Cellophane used for wrapping is made by this same process. However, the viscose, instead of being forced through the tiny holes of a spinneret, is squeezed through the long, narrow slit of a metal plate. A soft, pliable, transparent sheet emerges of a thickness which may be less than one-thousandth of an inch.

Acetate is another type of rayon and differs from viscose rayon because the original pure cellulose used is first chemically treated with acetic acid or vinegar, changing it into an entirely new chemical compound called cellulose acetate. This compound, like cellulose itself, will not dissolve in water but will dissolve in a liquid called acetone. This solution is also forced, like the viscose of rayon, through a spinneret. A current of warm air causes the solvent acetone to evaporate, leaving a solid filament of the fiber named acetate. Arnel is another type of cellulose acetate. Only about 10% of all rayons manufactured are of this type.

Rayon is actually a dissolved cellulose. The natural cellulose from which it is made is a compound which has not really undergone any chemical change. The product is, therefore, a man-made product rather than a truly synthetic one. The introduction of rayon was nevertheless a great achievement of the chemist. Yet many chemists were not completely satisfied. They had not created a truly synthetic fiber as they had done in the rubber adventure; they had only taken a highly complex organic compound from nature and regenerated or dissolved it.

This feat was hardly anything to crow about. If they had synthesized cellulose, and then made a fiber out of it—well, that would have been something else again, something they could honestly brag about. No one had quite accomplished this yet, though many had tried for years. Unlike man, the silkworm, chewing away at raw cellulose until it was ready to burst, was blessed with special enzymes in its digestive apparatus which enabled it to assimilate cellulose and then change it chemically. It used not cellulose but a sticky liquid which is mainly fibroin to make its silk. This is a protein which man has been unable to synthesize, and hence he could not imitate the silkworm.

What the chemist kept dreaming about was a fiber, wholly synthetic, one he could build up from ordinary chemicals which could themselves be synthesized. Some researchers came almost within sight of their goal, but only one finally reached it. In 1939 E. I. du Pont de Nemours and Company began to manufacture, on a full commercial scale, a fiber made from coal, natural gas, petroleum, and air and water. This fiber is as much a household word today as is cotton or wool. Du Pont looked for an appropriate name for it. Among the four hundred suggested was *norun*. This, however, was abandoned because it was realized that this fiber would have many uses other than for hosiery. Finally the pleasant-sounding name *nylon* was coined and arbitrarily chosen for this synthetic fiber.

Eleven years before, a chemistry instructor at Harvard University in his early thirties had somewhat reluctantly left the classroom to devote full time to research for du Pont. His name was Wallace Hume Carothers. He was born in Burlington, Iowa, of Scottish and Scotch-Irish descent. After taking courses in accountancy and secretarial studies taught by his father, he entered a small college in Tarkio, Missouri, and in 1924 took a doctorate in chemistry at the University of Illinois. He was a brilliant student, thorough and imaginative, a tireless worker, possessed of a rare and original mind.

He taught for a few years at the University of Illinois and at Harvard, where he was selected by du Pont to direct a program of chemical research at their newly es-

tablished Experimental Station at Wilmington, Delaware. Here, on the banks of the Brandywine, at the suggestion of Thomas Jefferson back in 1802, a small powder mill had been set up. It was established by Éleuthère Irénée du Pont de Nemours who, as an apprentice of Lavoisier, had learned how to make fine powder at Essone in France before he left for America. E. I. du Pont de Nemours and Company had prospered in the new land, and understood the value of scientific research.

Carothers had decided to throw his lot into what he hoped would be a more absorbing field of work, one that would fit his nervous, brooding temperament better. He had already become interested in polymer chemistry at the University of Illinois, and his first assignment at du Pont was connected with the pioneer work of Father Nieuwland which ultimately had given neoprene rubber to the world. Even before it was ready for the market, Carothers had turned to further basic studies of polymers. Eventually he wanted to try his hand at making a synthetic fiber. Du Pont had been interested in that product, stood ready to give him the wherewithal for such a project for they had complete confidence in his ability, and lots of money to spend.

He started work on fibers in 1931. Before the end of four years of research and development in this field, at the annual meeting of the American Chemical Society at Buffalo, New York, Carothers and his assistant, Julian W. Hill, made an interim report on their work progress. Their results to that date, they reported, "clearly demonstrate for the first time the possibility of obtaining useful fibers from strictly synthetic materials."

There were plenty of skeptics, of course, but even they realized that the power and wealth of a great chemical industrial empire was behind the effort. Perhaps it would come, but not within their lifetime. It was too complex a problem. Du Pont kept throwing more and more money and more and more assistants into this gamble. Eight more years of research and development passed, years of sweat, blind alleys, sudden illuminations, hope and despair.

While Carothers was still doing graduate work in Illinois, chemists had reported that natural fibers consisted

of a simple repeating pattern or polymer. Plastics, too, were all high polymers, and the plastic industry was growing into a giant almost overnight. A plastic is an organic substance, generally synthetic, that can be given a more or less permanent shape by the use of heat, pressure or both. It had very humble beginnings. In 1868 John Hyatt, an Albany printer and son of a village blacksmith, set out to make a substitute for the ivory piano key and billiard ball. Ivory from the tusks of elephants was getting scarce and more expensive than ever. After a long series of unsuccessful trials he blended one organic compound—natural camphor from the camphor tree of Formosa—with another organic chemical, cellulose nitrate, first made from cellulose in 1845 by Christian F. Schönbein, a German. Out of this chemical blend after controlled heating came celluloid, the world's first widely used synthetic plastic of industrial interest. Cellulose nitrate had been turned into a plastic 13 years earlier in England.

The stiff, white, breakable, and quite combustible celluloid collar of the gay nineties, and the Bakelite panel of the early radio cabinets are but two examples of plastics, of which there are now hundreds of types. In 1960, an estimated 7 billion pounds of these plastics were manufactured—more even than any single metal except iron.

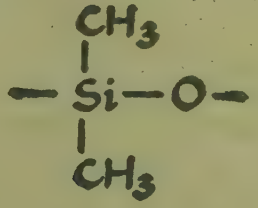
There are two broad groups of plastics. The first consists of substances that are softened by heat and molded by means of heat and pressure, becoming soft just as often as sufficient heat is applied. Your plastic eyeglass frame is a good example. Such plastics may be remelted as often as desired, and are called thermoplastics. Among them are polyethylene, the cellulose derivatives pyralin and tenite, saran, and lucite. Nearly all synthetic fibers, too, are thermoplastic.

The second group consists of substances that are softened by heat during the making of a plastic article, but, after cooling, cannot be melted again. They are the thermosetting plastics, such as Bakelite and formica. They are made from a variety of raw material such as the casein of milk, urea, fibrinogen which is a protein found in blood, and the protein of soybean. The properties and uses of plastics are almost limitless. A billion pounds of polyethy-

lene plastic, for example, are used annually to make insulating and packaging material, including flexible or "bouncing" bottles used so widely as containers for deodorants, cologne, hand lotions, and sprays. These squeeze bottles are a great packaging advance. Polypropylene is another fast growing thermoplastic.

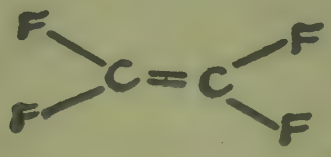
Many plastics are oil-soluble and are used in paints, lacquers and other finishes. Some are lighter than aluminum; others are tough enough to stop a bullet; many are resistant to chemicals, are electric insulators, and can be machined on a lathe, milled, ground, sawed and drilled with woodworking tools—a boon for the millions of do-it-yourself addicts. They have replaced many metals, wood and even natural fibers. The manufacturing chemist today can come up with a plastic of almost any reasonable specifications.

The silicones represent another new family of plastics, the so-called "bouncing putty" variety. They are polymerized carbon compounds in which the carbon atom has been replaced by the atom of the element silicon. The silicones are very inactive chemically, and can stand both extremely high and extremely low temperatures. Their resistance to heat is so much greater than that of the carbon-based plastics that they have found increasing use in making items such as gaskets. Some silicones can be vulcanized in very much the same manner as rubber. They have also been used in greases, lubricants, paints, varnishes, as water repellents, and, suprisingly enough, as pan-glaze to keep bread from sticking to pans in bread factories. They are, like the other plastics, long-chain polymers having the general formula



It was well known that plastics, rubber, and even synthetic fibers are all high polymers and not intrinsically different. If the chemical forces between the chains of molecules of which they are built are weak, we get a rub-

berlike substance. If the chemical attractions are strong and the chains fit easily into a regular pattern, we get a fiber. If the chemical forces are intermediate, we get a plastic. Some high polymers are actually used as rubber, fiber, and plastic. Polyethylene, for example, first synthesized in England in 1933, is very widely used as a substitute for rubber for covering electric wires and cables, as a plastic in transparent bags, pipes, cups, saucers and other housewares, and as a fiber in making filter cloths which resist the action of strong acids. The identical plastic is found in the synthetic fiber dacron and in the electric insulator plastic known as mylar. Du Pont's teflon, made by polymerizing tetrafluoroethylene,

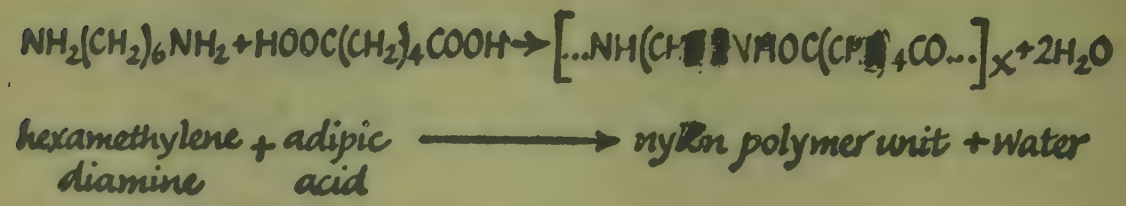


is also an excellent electric insulator, and is used in bearings and in valves for handling acids and other corrosive liquids. A fabric of teflon fiber is often double woven with a backing of nylon or cotton.

Carothers, of course, was aware that natural and synthetic fibers both possessed simple, repeating molecular patterns or polymers. It was well to keep that fact clearly in mind, and to try to find the secret of how nature manages to latch small groups of atoms on to each other in long chains. After much thought and experimentation he decided to put his company's money on diamines and dibasic organic acids as the building blocks of his new synthetic fiber. A diamine contains two NH_2 groups. A dibasic organic acid contains two COOH groups. He prepared a number of diamines and finally chose hexamethylene diamine, which could be obtained by synthesis from a plentiful source—natural gas or petroleum. For the dibasic acid he selected adipic acid, which could be synthesized from another almost limitless source—phenol of coke ovens.

Early in 1935 he finally succeeded in synthesizing a high polymer from these two chemicals to form a molecule

containing as many as one thousand atoms with a molecular weight of about 10,000. It bore some resemblance actually to the structure of natural silk. The equation for the reaction in which one of the units of this polymer is formed may be written as:



The thick, molten nylon produced by this reaction is forced through the tiny holes of a spinneret to form the thin fibers from which nylonware is made. Here was the end of the road, reached after many years of effort and an expenditure of $20 million.

Carothers had, in the meantime, published a score of classic papers in the field of high polymers and had taken out many patents for du Pont. The chemical world had learned to have a very high regard for this silent, sensitive, melancholy man. He traveled to England in 1935 to read a paper on polymers before the Faraday Society, and was elected a Fellow of the Chemical Society of England. Honors came to him also in America. The following year he was elected a Fellow of the National Academy of Sciences in the United States, a signal honor—the first organic chemist outside of academic circles to be elected to this body. A year later, he came to a sad and premature end two days after his forty-first birthday. In less than ten years of intensive research he had piled up a brilliant record of achievement.

When nylon came on the market, it set off a minor revolution, especially in the women's hosiery market. Nylon was stronger, tougher, more water resistant, more elastic, and dried more quickly than natural silk. Women were ecstatic over its beauty, washability, and relative indestructibility. Full-fashioned and seamless nylon stockings replaced silk stockings as fast as they became available. Women boasted about the nylon stockings they had worn for a whole year which were still in excellent condition.

That was only the beginning. Shirts, dresses, socks, underwear and other apparel were offered to the public in nylon, and they were gobbled up. Curtains, too, fishing lines, nets, brushes, window screens, tubing and a hundred and one other items were fashioned from this new, truly synthetic fiber born in the chemist's test tubes.

Although for a time a proprietary name, nylon is now a generic term, like "glass." It soon became the name not of one chemical but of a class of compounds of similar structure, depending upon which dibasic acid and which diamine were used in the synthesis. Here was a new landmark in creative chemistry.

Once the breakthrough had been made by du Pont, other manufacturers jumped into the field. The nylons turned out to be only the vanguard of a host of synthetic fibers that marched out of factories during the next few years. Du Pont followed with orlon and dacron. The orlon fiber is substantially a polyacrylonitrile manufactured from a chemical which is synthesized from natural gas, ammonia, and air. Dacron is the child of two petrochemicals derived from crude oil. One of them is ethylene glycol, commonly used as an antifreeze in automobiles; the other is terephthalic acid. It has a tight structure with few openings through which water can pass. It therefore resists water penetration very well and dries quickly. It looks like wool, has high resilience, and resists wrinkling. Dacron suits require only infrequent pressing. It is also mildew and moth-resistant. This fiber is made in England under the name of terylene.

The Union Carbide and Carbon Company's contribution in this field was a synthetic fiber named dynel. This is manufactured from the same acrylonitrile used in making orlon, but it is a copolymer, the other monomer being a compound known as vinyl chloride whose formula is $CH_2{=}CHCl$. Dow Chemical Company, pioneer in the extraction of magnesium from the sea, was also represented in the synthetic fiber race. Dow's entries were named zefran and saran. The latter is the copolymer son of the same vinyl chloride used in dynel, and another chemical named vinylidine chloride (CH_2CCl_2). Saran is highly resistant to the effects of light, heat, and chem-

ical agents, and also absorbs little moisture. The Chem strand Corporation entered its own favorite named acrila which is light, resilient, pleasant to touch, and preferr by manufacturers of sweaters and sports shirts and oth wearing apparel. It is manufactured from the same acryl nitrile used in making orlon and dynel. B. F. Goodric Chemical Company's new fiber is darlan made from viny idine dinitrile. American Cyanamid announced its acryl fiber Creslan and Tennessee-Eastman produced Vere another acrylic fiber. Avril and Zantrel were later arrival By 1960 at least 55 synthetic fibers were listed.

There was no stopping the synthetic-fiber chemist. H tried for wool substitutes from proteins, since natural woo is an animal product that is protein in nature. The first o these wool-like fibers was made in Italy back in 1936 fron the casein of milk. It was named Lanital. Vicara is th trade name of an American synthetic fiber which is als made from zein, a protein extracted from the kernels o corn. Even the lowly peanut was called upon to contribut its protein matter for the test-tube birth of another woolly fiber in Britain, where it was first manufactured as ardil Experimental fibers have been released which are made from soybeans, egg albumin, and even from the protein keratin extracted from feathers. There is no telling whose privacy will next be invaded by our ambitious chemists to make fluffy, warm, serviceable textiles for all of us.

The superior properties possessed by individual syn- thetic fibers in comparison with the natural fibers of cotton and wool have led to their ever-widening use as blending fibers, not only for clothes but also for other fabrics used in rugs, draperies, awnings, and blankets. Combinations of natural and synthetic fibers have been found to add desirable characteristics to blankets, rugs and carpets which are now woven of rayon and natural wool. Nylon, the most abrasive-resistant fiber of all, has been added to cotton, wool, and rayon in amounts varying from 5 to 50% to make more durable fabrics. Equal amounts of ac- rilan and wool have been used to turn out slacks and other apparel. Men's suits are made from a mixture of wool and dacron, and tropical suits have been fashioned from a mixture of orlon, viscose, and acetate rayons.

Wash-and-wear summer clothes for men are made from a blend of dacron and cotton, or orlon and cotton. They wash easily, dry quickly and require little or no ironing. Garment manufacturers are still looking for a better wash-and-wear fiber for tailored clothing.

These new fiber mixtures were a headache in the beginning. Problems of dyeing and cleaning plagued the manufacturers and dry cleaners, since each fiber had its own characteristics and eccentricities towards color and solvents. Gradually however these problems, too, were solved.

Economic bugs soon appeared on the scene—troublesome problems that needed additional time for adjustment. For instance, man-made fibers in 1954 caused a sharp downward trend (25%) in the use of wool for both men's and women's clothing. A downward trend of 14% in the use of wool by carpet mills was noticed that same year. The synthetic fibers soon were competing with each other. For example, rayon quickly replaced cotton in the cords of automobile tires and helped increase the average mileage of our rubber tires. Nylon manufacturers saw this huge new market and soon pressed hard to take the place of rayon, not only in this lucrative field, 50% of which they controlled by 1962, but also in certain types of apparel and home furnishings.

There were even much deeper economic effects of the fiber revolution. In 1940, 85 million pounds of raw silk were produced by Japan and China. This output provided 40% of the foreign exchange earned by all of Japan's exports that year. We bought 85% of the 85 million pounds. Twelve years later raw silk imports by the United States had dropped to a mere 5% of this figure. Nylon was responsible for this nose dive. Today Japan is still struggling to avoid catastrophe in her silk industry. More than two million Japanese farmers remain engaged in sericulture. Japan is trying to increase its consumption by blending it with other fibers. China faces the same dilemma. Our present annual consumption of the natural product is still menacingly low—about five million pounds—and it appears that the battle is lost.

Japan is using more and more of her arable land for

food instead of for mulberry trees. With the ever-grow consumption of both man-made and synthetic fibers come other far-reaching effects. This aspect of creat chemistry will, in time, even change the agricultural p terns of other great centers of cotton and wool producti For example, a perennial cane which grows easily in It furnishes immense quantities of cheap cellulose for t Italian rayon industry, thereby freeing Italy of the ne to import fir and spruce from Norway and Sweden. O pound of chemical cellulose can make one pound of rayo "Is it not, therefore, reasonable to believe," asked o leader in the investment field, "that nations vigorous developing a home textile industry will prefer to impo chemical cellulose than to purchase cotton or wool at fo to twenty times the cost?"

In the United States, total civilian per capita consum tion of fibers has shown a steady increase. The consum tion of cotton has remained almost stationary, that of wo has actually declined a bit, while that of the artificial fibe has jumped phenomenally from 0.6 pounds in 1925 13.5 pounds in 1960. Of the more than 7 billion poun of fibers used by the American people in 1960, 2 billio pounds, valued at more than a billion dollars, were sy thetic fibers. This represents more than 28% of the tota

Both production and consumption of fibers differ ver widely around the world. Our own per capita consump tion is by far the greatest in the world, amounting to abou 40 pounds. Next comes Britain with about half th amount. Japan's consumption is approximately 5, China is a pitiful half a pound, and Burma is just about one tent of a pound. Of course, many factors, including climat account for this wide range, but it is also true that th amount of fiber consumed is almost a measure of the ad vance of a country.

No world-wide dislocation, however, is anticipated, fo the present production of all synthetic fibers constitute only about 15% of the 31 billion pounds of cotton, woo and silk grown around the world. If we omit the rayon which represent the bulk of our man-made fibers, the per centage drops to only about one per cent. Cotton is sti

the workhorse of the fibers, and natural wool has hardly begun to feel the encroachment of synthetics.

Having penetrated the cotton plantations, devastated the mulberry orchards, and infiltrated the sheep ranches, the synthetic chemist now eyes the timber forests of the world. Du Pont has already reported the successful manufacture, on a laboratory scale, of ordinary paper out of the synthetic fibers of nylon, dacron and orlon. This paper is ten times stronger than the paper now in general use. It is more highly resistant to chemical attack, absorbs less moisture, and resists the action of molds, bacteria and light much better than does ordinary paper. In the beginning it will lend itself to the manufacture of wrapping paper, maps, tracing paper, records and documents. Eventually it may even replace wood pulp for newspapers and rag paper. The cost is still too high, but the main manufacturing hurdles have been cleared.

Another new development in this field is the emergence of the nonwoven synthetic fabric. It appeared on the market in 1945 and in a little more than fifteen years reached a production figure of 100 million pounds. Like felt this fabric requires no spinning or weaving of fibers. Instead, the fibers are combined by heat or adhesives. This nonwoven fabric is used for interlinings, window shades, aprons, table cloths and even hoop skirts. It may even usher in the throwaway apparel era when inexpensive children's and household dresses, and nurses' uniforms will be made of such fabrics.

Watch out for those synthetic chemists. They have been known to show up in the most unexpected places to interfere suddenly with the sleep of many a complacent corporation executive.

10 The New Elements of Mode
Alchem

WITH an amazing parsimony the chemist, using less tha half a dozen elements, has as you have seen fashione thousands of new chemical compounds and imitated an even improved on nature in scores of instances. With few additional elements he has built a complex industria world out of such metals as steel, copper, and aluminum After centuries of toil he finally, in 1945, found the las of the 92 chemical elements which man had inherited fo better or for worse.

When the news was flashed around the scientific worl that the last of the chemical elements had finally been iso lated and identified, there was a warm feeling of satisfac tion in laboratories all over the globe. But Frederick Soddy one of the architects of this completed mansion, bemoaned the fact. "The chemist," he said, "cannot but feel like Alexander that something of the zest of life has departed, for the discovery of new elements, like the discovery of new worlds, has always been a powerful incentive." As it turned out, however, Soddy was wrong. There were other observers who disagreed, like his countryman, the philoso pher-mathematician, Bertrand Russell, who as early as 1923 said, "No reason is known why there should not be more complex atoms, and possibly such elements may be discovered some day." They would be unearthed in in finitesimal quantities in hidden, unexpected places. Per haps, only fleeting glimpses would be seen of them. Maybe, the boldest ventured to predict, they might even be syn thesized out of existing elements. And this near miracle actually came to pass.

To understand this tremendously exciting achievement of science, we must retrace our steps and get a thoroughly revised picture of the cosy little simple model of the atom that men taught just before the close of the last century.

The 1803 model of the Daltonian atom was an indivisible, impenetrable, indestructibly solid sphere. It served chemistry well for almost a hundred years. No rival model seriously challenged it. Suddenly a whole train of discoveries, many of them accidental, exposed the hidden springs and complicated machinery of the not-so-simple atomic world of the Manchester Quaker.

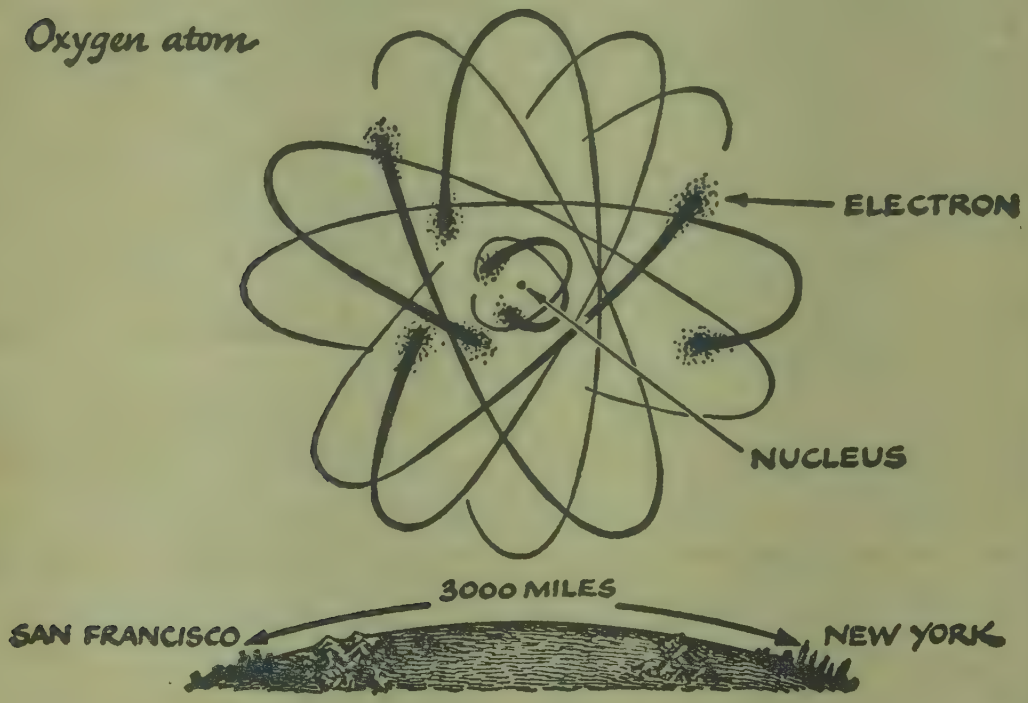
Among these earlier discoveries none stirred the world so deeply as did that of the isolation by Marie and Pierre Curie of a new element, radium. Radium was a metal that glowed in the dark, gave off heat constantly, shot out rays and particles more penetrating and deadly than any rays known, caused bad burns, gave birth to a constant stream of electrified atoms of helium, and ejected a flood of tiny particles of negative electricity which were identified as electrons. And during this reckless and lavish giveaway it was slowly changing from radium to an entirely different element, lead.

Evidently the atom of radium was a very intricate mechanism with a maze of different parts. The old concept of Dalton was shattered to bits. Within a few years the evidence for this was overwhelming. First, in 1897, an Englishman, Joseph J. Thomson, in the Cavendish Laboratory of Experimental Physics in Cambridge of which he was director, discovered that the electron was a part of every atom. This particle turned out to be an extremely light unit of negative electricity, the mass of which was only 1/1836 that of the mass of the hydrogen atom, the lightest known.

Fourteen years later, one of Thomson's pupils, Ernest Rutherford, who had come to the Cavendish Laboratory from New Zealand on a scholarship, demonstrated that atoms also contained another component, which he named the proton. A proton is a particle of positive electricity, with a mass approximately that of the hydrogen atom. Then in 1932 another Briton, James Chadwick, fulfilling a prediction of both Rutherford and an American scientist at the University of Chicago, picked out another basic particle of the atom which was named the neutron. This unit was electrically neutral, and had a mass very much the same as that of the hydrogen atom. It was itself com-

posed of one electron and one proton so tightly packe and held together as to appear as a single particle with density millions of times greater than that of the heavie element. No circus strong man could even budge as litt as a thimbleful of this revolutionary bit of matter.

Innumerable and ingenious experiments coupled wi clear and bold reasoning finally produced a blueprint the new atomic architecture. Each atom, except that the lightest form of hydrogen, contained one or more each of these three basic ingredients. Electrons, proton and neutrons were arranged in different patterns in eac of the 92 different elementary atoms. In the very cente of each atom, whose diameters ranged from about 1/40 000,000 to 1/10,000,000 inch, was an even much tinie core made up of protons and neutrons packed closel together in a space with a diameter only 1/100,000 tha of the atom. This core is the nucleus whose existenc Rutherford established by experiment.



The dense pinpoint or nucleus inside the atom gave the element its mass or weight as well as its other physical characteristics. Outside the nucleus, at a relatively great distance from the center and moving in concentric orbits, were all the electrons of the atom. The arrangement of

these electrons in concentric shells around the nucleus determined all the chemical properties of the element. In between the nucleus and the rings of electrons was a relatively immense void—empty space—so vacant, in fact, that the atom resembled a net of gossamer thread that is disorderly all holes.

The electrons around the nucleus were by no means fixed in position. They were in constant motion, zooming around at tremendous speeds in different orbits. It was this particular structure of the atom that led Rutherford to speak of the atomic universe as a miniature solar system with the nucleus representing the sun and the many electrons as the planets revolving around the sun. It was the speed of the electrons around the nucleus that prevented them from falling into the center which was charged positively, just as the earth and the other planets in their elliptical courses around the sun are prevented from being pulled into the massive sun by gravitational attraction.

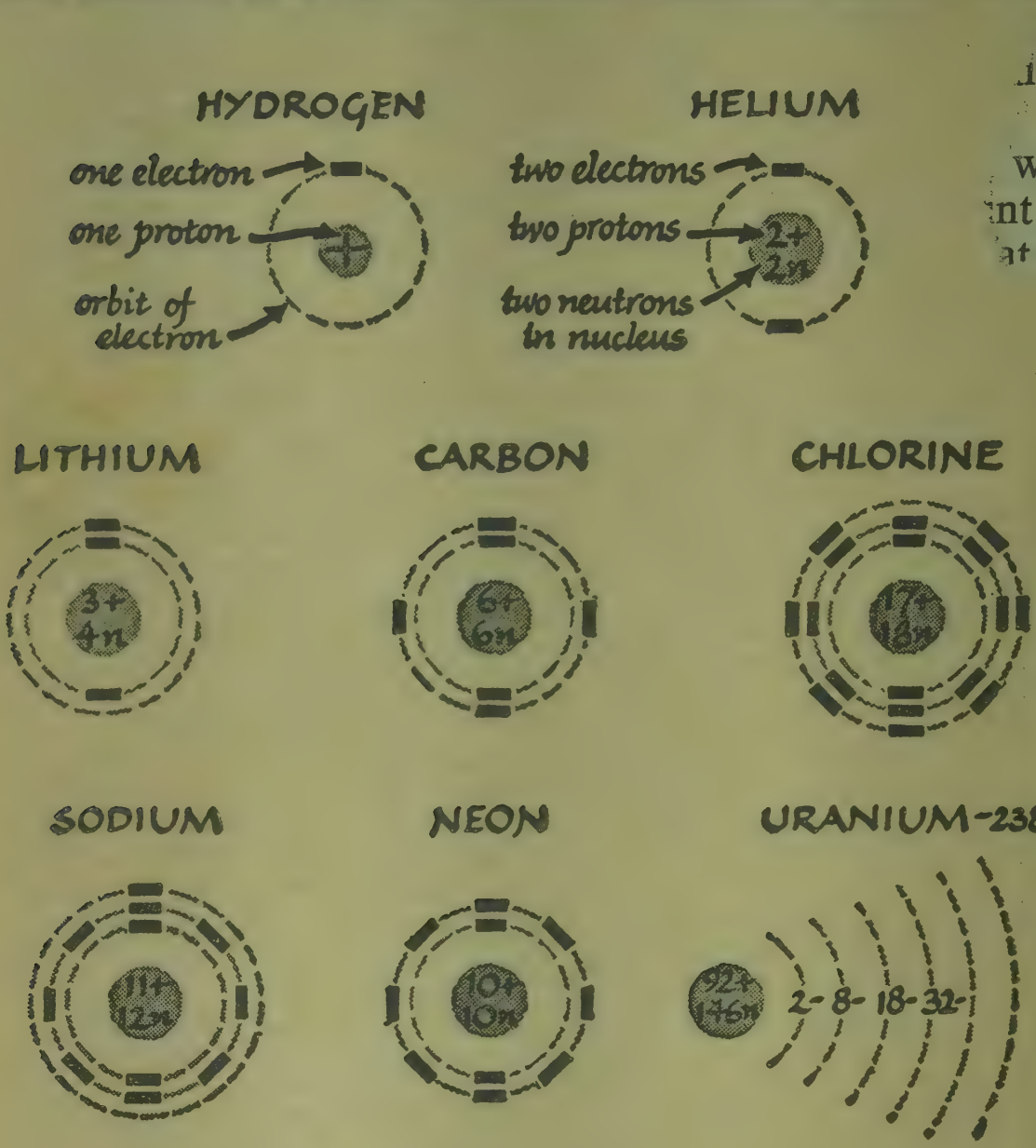
The jetlike and perpetual motion of all the electrons of each atom also accounts for the solid behavior of this huge emptiness of an atom. Said Sir William Bragg, another pioneer in the field of the atom's structure, "It is strange to think of an atom as being empty as a solar system, not a hard impenetrable body but a combination of nucleus and electrons which occupies a certain space somewhat as an army occupies a country. The bodies of the soldiers do not fill the country from boundary to boundary; but enemy soldiers may not enter nevertheless."

Now let us see how the chemist pictures the atoms of several different elements according to this solar-system model of the atom. Hydrogen, the lightest element, has one proton and one electron, sodium has 11 electrons and 11 protons, and uranium, heaviest of the natural elements, has 92 electrons and 92 protons.

You will note, first, that the number of electrons and the number of protons in each different atom is the same. This must be so because the atom is normally electrically neutral, and there must not, therefore, be an excess of either electrons or protons which have opposite electrical charges.

You will also note that the number of protons in each

different atom is the same as the numerical position o
that element in a list of chemical elements shown in th



complete Periodic Table of the elements on pages 196-197. The position of the element is known as the *atomic number* of that element. Thus hydrogen has an atomic number of 1, sodium 11, chlorine 17, and uranium 92. The fact that each succeeding element possesses one additional proton in its nucleus was discovered by another student of Thomson in the Cavendish Laboratory in 1912. Soon afterward this young man, Henry G. J. Moseley, was permitted by a shortsighted government to enlist in the British Army during World War I. A few months later, in the summer of 1915, a Turkish bullet at Gallipoli ended this career of this genius at the age of 27.

Periodic Table of the Chemical Elements and saw that it was good. With the boldness of a prophet he declared that the accepted atomic weight of tellurium was wrong; that it must be between 123 and 126 and not 128 as its discoverer had determined. Years later, this discrepancy was cleared up.

Then he detected another apparent contradiction in his table. Here was gold with the acknowledged atomic weight of 196.2 placed in a space which rightfully belonged to platinum, whose established atomic weight was 196.7 Again he claimed an error. And again the balance of the chemist came to the aid of the philosopher, for the then accepted weights were wrong and Mendeléeff was right once more. Gold had an atomic weight greater than that of platinum. This Russian's table was almost uncanny in its accuracy.

Mendeléeff was still to throw his most crackling bolt. There were several places in the table that were vacant. Were they always to remain uninhabited or had the efforts of man failed as yet to uncover some missing elements that belonged in these spaces? A less intrepid person would have shrunk from the conclusion that he drew. Not this Tartar, who would not cut his long hair even to please the Czar. He believed in his table and scorned the skeptics. He declared that three elements would be discovered to fill these empty spaces. He spelled out their physical and chemical properties and even gave them interim names. And men went in search of these questionable elments in the bowels of the earth, in the flue dust of factories, in the waters of the oceans, and in every corner of the globe.

The chemical world waited for the final test, but not for long. For in 1875 in a zinc ore mined in the Pyrenees, Lecoq de Boisbaudran came upon the first of the missing elements. It fitted exactly the description of the Russian, and it was named gallium after the native country of the discoverer. Then came two more of the missing elements —germanium and scandium—exactly as Mendeléeff had predicted. Mendeléeff and his table were completely vindicated.

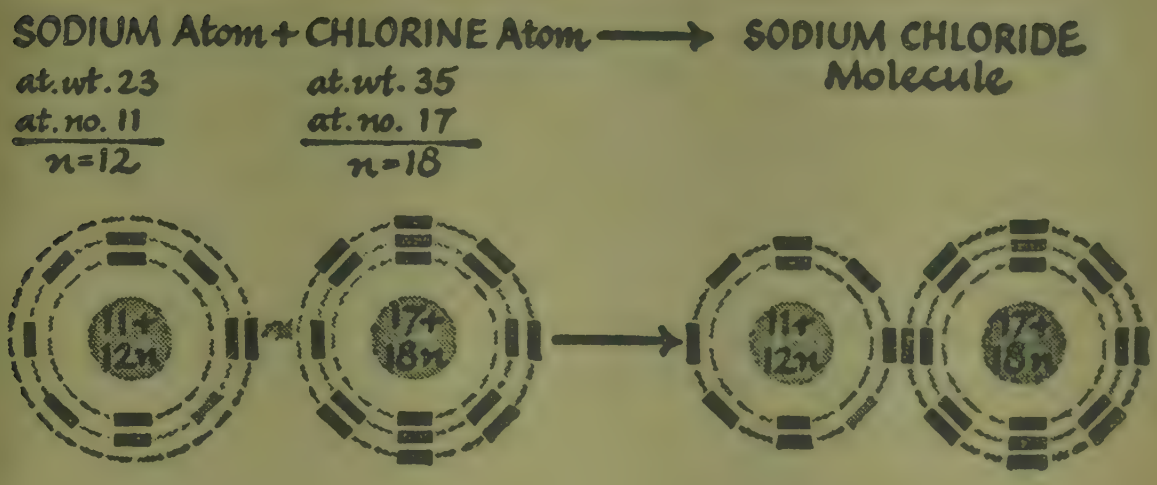
Let us again examine this table (pages 196—197)

which has been brought up to date to include also all th elements discovered since Mendeléeff's time. You wi notice that the first two elements, hydrogen and helium are in a small group by themselves. This is followed by a group of eight elements starting with lithium and ending with neon. A second batch of eight elements follows the one, consisting of the elements sodium through argon. The next two periods of elements number 18 each. The sixth collection is the largest with 32 members, including 14 rare-earth elements.

The existence of this order of 2, 8, 8, 18, 18, and 32 elements led two American scientists—Irving Langmuir, formerly of the General Electric Research Laboratories, and Gilbert N. Lewis, professor of the University of California—to suggest the present accepted arrangement of electrons outside the atom's nucleus. This contribution has proved of inestimable value in understanding a host of chemical observations hitherto apparently unrelated. To begin with, a chemical change is understood today to be simply a shifting or sharing of electrons in the outermost ring of electrons to complete that ring. No other part of the atom is involved. For example, the sodium atom has only one electron in its outer ring, whereas the chlorine atom has seven electrons in its exterior ring. It appears that the main desire of every atom is to complete the ring farthest from its nucleus. Hence the sodium atom is very eager to give away this single electron that makes up its outermost ring and thus leave it with a complete ring of eight electrons. The chlorine atom, too, is eager to pick up one electron to complete its outlying ring of seven electrons and make it a full eight-electron ring.

Under these conditions, when an atom of the metal sodium comes in contact with an atom of the nonmetal chlorine there is a violent commotion of the electrons in the outermost rings of both atoms, which ends in a shifting of the lone electron of the sodium atom to the single empty position of the seven-electron ring of chlorine. As a result of this shifting of an electron, a chemical compound sodium chloride is formed, each portion of which has a full complement of electrons in its outermost ring. The atoms are now completely satisfied, and the salt com-

pound formed is a perfectly stable and happy one. This chemical change may be represented as follows:



The sodium atom has one electron in its outer ring. Its valence is + 1. It is a very active metal.

The chlorine atom has seven electrons in its outer ring. Its valence is therefore − 1. It is a very active nonmetal.

The ion-molecule structure of the sodium chloride compound contains both sodium and chlorine particles. The outer ring of each is complete; and the compound is, therefore, very stable.

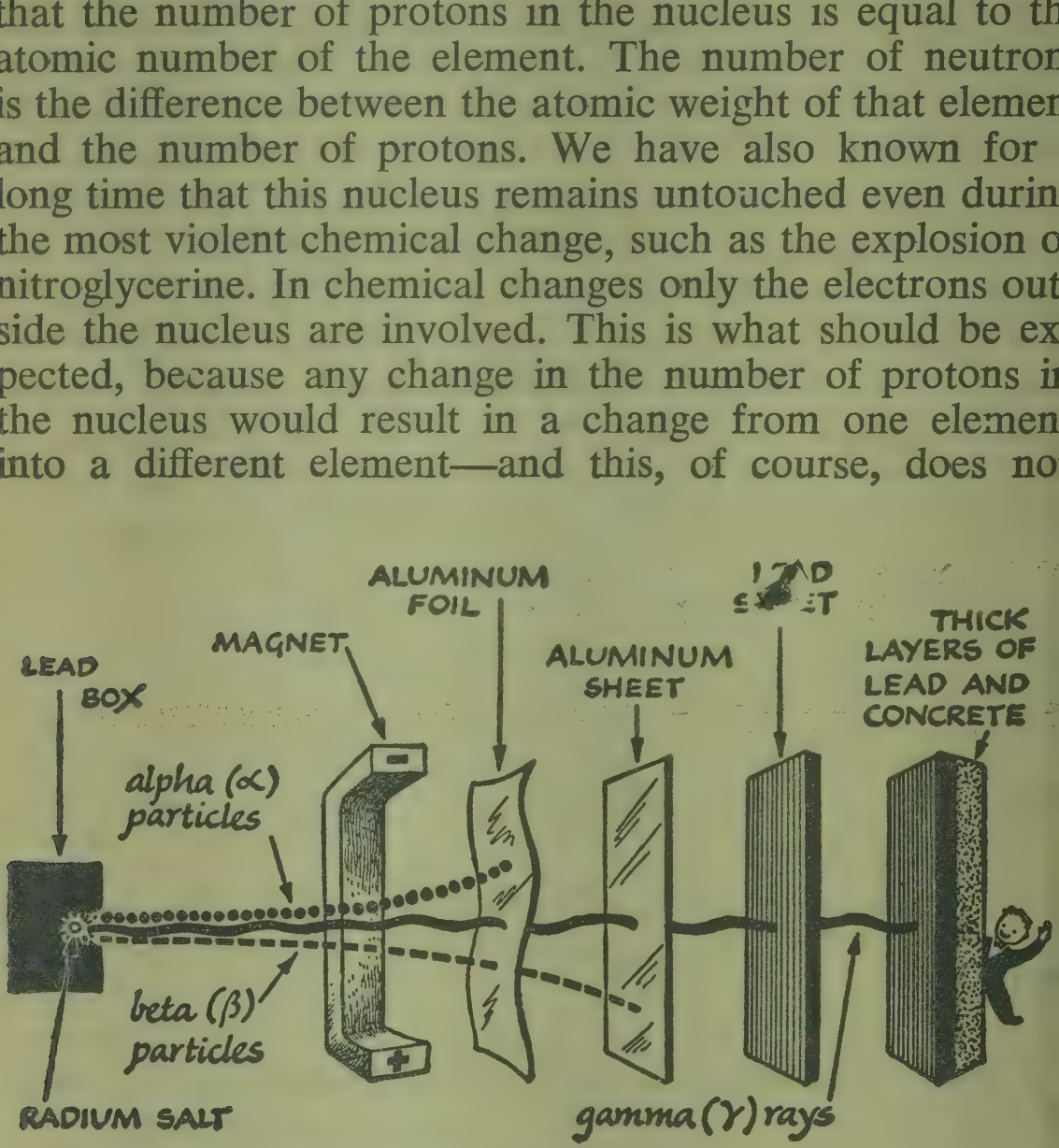
The fewer the electrons involved in the commotion the greater the chemical activity of the element. Aluminum, for example, with three electrons in its outermost ring is less chemically active than sodium. Helium, neon and several other elements with complete outer rings show no desire to shift electrons; hence they are chemically inert —that is, under no conditions will they combine with other elements. Accordingly, no stable compounds of these elements are known.

Our understanding of what valence means has also been clarified. Valence is simply the number of electrons an atom must lend or borrow to complete its outermost ring. For example the valence of sodium is one, since it can lend only one electron. The valence of chlorine is also one, since it can borrow only one electron. The valence of oxygen is two, since it needs two electrons to join with the 6 electrons it has on its outer ring to make a stable eight-electron combination.

We also now have a new definition for a metal and a nonmetal. A metal is an element which will "lend" elec-

trons—one whose outermost ring has one, two or thr electrons which it can give away. A nonmetal is an eleme whose atom has 5, 6, or 7 electrons in its outer ring ar needs to "borrow" electrons to get the full compleme of 8 electrons and thus form a stable configuration.

While scientists have learned a great deal about th electrons in atoms, much less is known about the mor complex details of the atom's nucleus. Most of what we d know about this hard core of the atom we have learne within the last few years. We have known, for example that the number of protons in the nucleus is equal to th atomic number of the element. The number of neutron is the difference between the atomic weight of that elemen and the number of protons. We have also known for long time that this nucleus remains untouched even durin the most violent chemical change, such as the explosion o nitroglycerine. In chemical changes only the electrons out side the nucleus are involved. This is what should be ex pected, because any change in the number of protons in the nucleus would result in a change from one elemen into a different element—and this, of course, does not



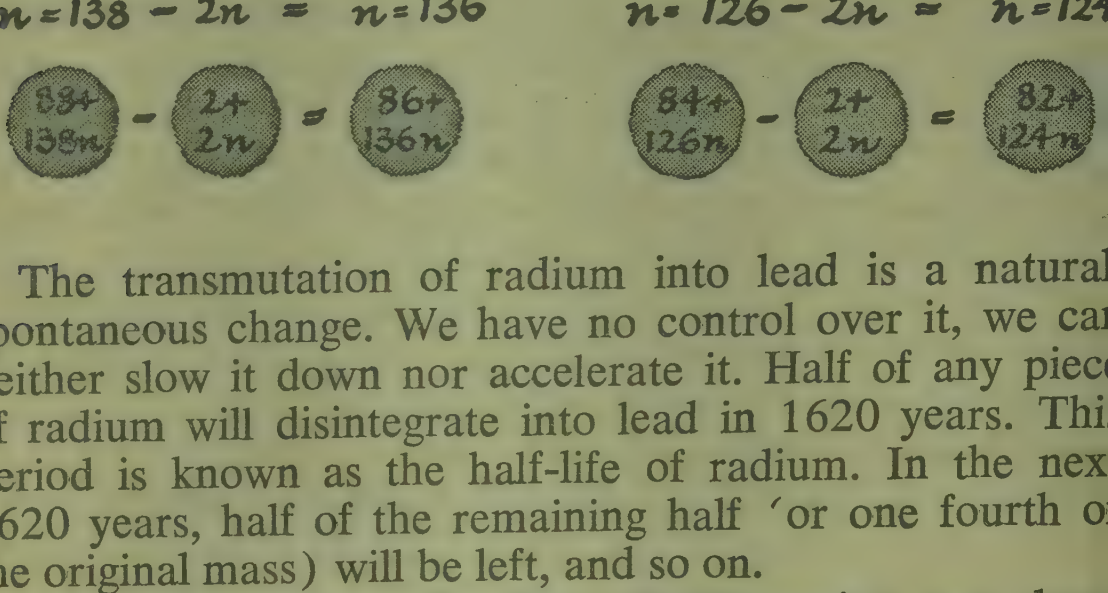
happen. The alchemists, you may remember, tried to change one element into another element (lead into gold, for example) and failed miserably in spite of centuries of toil.

A change of one element into another actually occurs, however, in a few instances. This change, called *transmutation*, occurs spontaneously in nature. The first evidence of this fact turned up when the Curies discovered the element radium. Scientists for the first time were presented with a most unusual spectacle, a perfectly pure and simple element throwing off rays and particles and finally disintegrating into a lighter element, lead. How did this happen? Rutherford and Soddy made the first correct explanation of this unusual phenomenon. Back in 1902 they declared that the electrons and helium thrown off by radium came from the breaking up of a very unstable or "unhappy" nucleus inside the atom of radium. This alteration of the nucleus of an atom is a much more deep-seated and serious change. It is known as a nuclear change, and, in the case of radium disintegration, takes place in several stages.

Radium is found in the 88th position in the Periodic Table of the Elements. It, therefore, has an atomic number of 88 and can boast of 88 protons in its nucleus. Its atomic weight has been determined as 226. Since this atomic weight is the sum of the number of protons and neutrons in its nucleus, radium contains (226—88) or 138 neutrons. Now this tight little world of the nucleus of radium is a very unsteady one. One of its members leaves home in the guise of a helium atom whose atomic weight is 4. This act of migration changes the radium atom into a different element called radon, with atomic weight 222 and atomic number 86.

After numerous additional internal quarrels, several other members are ejected, leaving a new element called polonium to take its place. This new element has an atomic number of 84 and an atomic weight of 210. Polonium was, in fact, the first chemical element discovered by Madame Curie and was named after her native country. Now polonium is still very jittery and disturbed, and before long it has ejected another helium atom from its nucleus and changed to still another different element—lead, whose atomic number is 82 and atomic weight 206. Some of these nuclear changes may be represented as follows (for the

purpose of simplification the outside electrons of the atom are not shown; only the nuclei are represented):


RADIUM – Helium → RADON ⟶ POLONIUM – Helium → LEAD
at.wt.226 – 4 = at.wt.222
at.no. 88 at.no. 86
n = 138 – 2n = n = 136
at.wt. 210 – 4 = at.wt.206
at.no. 84 at.no. 82
n = 126 – 2n = n = 124
88+ 138n – 2+ 2n = 86+ 136n
84+ 126n – 2+ 2n = 82+ 124n

The transmutation of radium into lead is a natural spontaneous change. We have no control over it, we can neither slow it down nor accelerate it. Half of any piece of radium will disintegrate into lead in 1620 years. This period is known as the half-life of radium. In the next 1620 years, half of the remaining half (or one fourth of the original mass) will be left, and so on.

When the process of radium disintegration was demonstrated to be nothing more than a change in the composition of an unstable nucleus, scientists began to wonder whether this process could be imitated by man in the case of elements with stable nuclei. Artificial transmutation, evidently, could be brought about by so disturbing or jolting the nucleus of an atom as to force it to eject parts of itself or receive one or more additional protons. But how to get inside the nucleus was a prodigious problem. First of all, it was so infinitesimally small that an even tinier "bullet" would have to be used. Secondly, the bullet to be chosen would have to be propelled at a stupendous speed to overcome the electrical defenses protecting the positively charged nucleus.

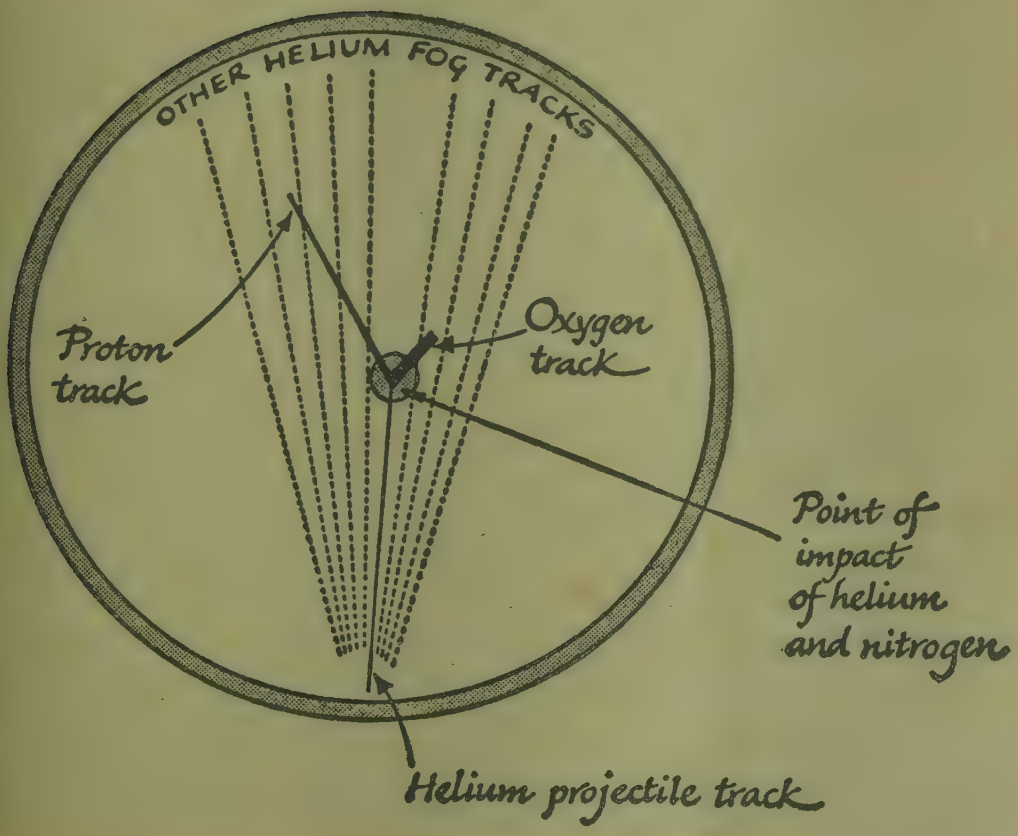
Rutherford came up with a possible solution. The discoverer of the proton and the nucleus, and the first man to explain correctly the strange action of radium disintegration, Rutherford knew his atomic particles. He knew the nature of the helium particle ejected from radium. This bit of matter, also known as the alpha particle, is composed of two protons and two neutrons and, having no electrons, is positively charged. Not only is it a tiny

projectile, but it has tremendous penetrating power, being hurled from the heart of radium at speeds greater than 10,000 miles per second—velocities that made the movement of a discharged rifle bullet seem like a slow walk in comparison.

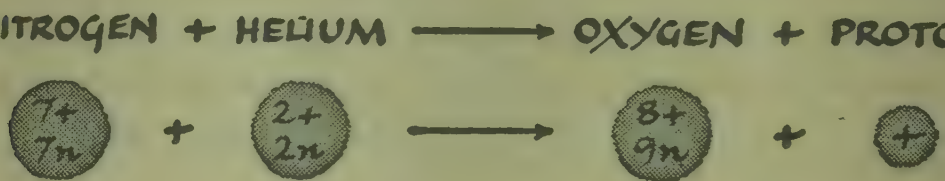
Inquisitive, effervescent Rutherford would try anything to pry open a secret of nature. Anyhow, it was an idea worth trying. He induced C. T. R. Wilson, one of his colleagues at the string-and-sealing-wax-Cavendish Laboratory, to help him with an improvement for his camera that might take pictures of what happened during this baffling assault on the subatomic world. Wilson had come through in 1905 with an instrument later known as a cloud chamber apparatus which turned out to be as important in the field of nuclear chemistry as the microscope is in biology or the telescope in astronomy.

Rutherford then went to work again. Using a speck of radium as the source of his tiny but mighty little bullets

Discovery plate of Rutherford's historic artificial transmutation of nitrogen into oxygen in 1919



of alpha particles, he hurled them at the atoms of nitro gas trapped in a flask. He did thousands of experime but success eluded him. Years went by and Rutherf kept at it. Even during the dark days of World War I research was resumed at odd moments when he co snatch time from heavy commitments he had made to military. Finally, one day in 1919, Rutherford got evidence he was waiting for. It was minute, fleeting, ficult to observe at first, but later unmistakably captu in the emulsion of a photographic plate attached to W son's cloud chamber. A broken line in the plate, known a fog track, told the story. An alpha particle had fou its tiny target, ploughed its way into the nucleus of nitrogen atom, ejected a proton from its inner sanctu and thereby changed nitrogen into a different eleme oxygen, with an atomic number of 8 and atomic weig of 17. This nuclear change may be represented as follows



Despite this epic achievement—the first artificial tran mutation produced by man—the world of science was sti not completely satisfied. After all, whispered some pe fectionists, Rutherford had used one radioactive eleme which was being transmuted by nature to produce h own transmutation. That wasn't fair. He had been com pelled to call upon nature for help. Suppose such an ele ment were not available. Suppose he did not have radium What then? What they wanted, and they made no bone about it, was a real, honest-to-goodness man-made trans mutation without benefit of radioactive radium and th swift bullets it supplied. They wanted nothing less tha a man-made projectile.

This was an impertinent and almost impossible reques It meant that scientists would have to manufacture a infinitesimal bullet with a speed never before even ap proached by man. To accomplish this, scientists woul

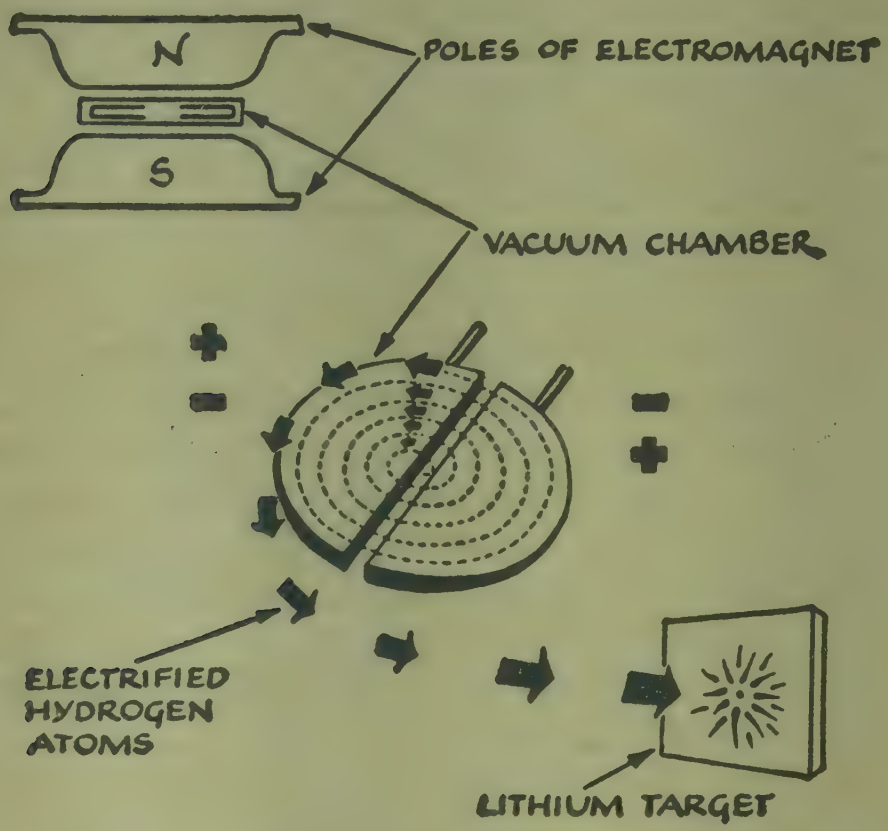
have to invent a machine capable of accelerating an electron, a proton, or a helium atom to velocities of the order of 10,000 miles per second and more. The wonder of it all is that science did come through with just such a machine.

At the University of California in Berkeley worked a young scientist named Ernest Orlando Lawrence. As a boy he had become interested in science through his hobby of radio. Overcoming first a hankering for medicine, he finally threw in his lot with the study of the nature of the atom. Late one evening in the spring of 1929 he quite accidentally came across an article by an obscure Norwegian research scientist who, until 1932, worked for the General Electric Company in Berlin. As he was attracted to a diagram of a piece of apparatus used by this physicist, something clicked in his mind and he never even finished reading the piece. He put it aside, took paper and pencil, and within a few minutes he was sketching a piece of apparatus and writing down dozens of mathematical formulas. The essential features of a new machine came to him almost immediately. The next morning he told a friend that he had hit upon a new idea, and was about to invent a new tool for science.

Within a few weeks he had converted his idea and his formulas into his first "accelerator" of tiny particles, which became commonly known as a cyclotron. It was a crude glass-sealing-wax affair which was soon followed by a small covered, frying-pan model, and then another one costing about $1,000. This 11-inch merry-go-round machine was capable of speeding up hydrogen particles as they rushed around a circular track, prodded along into ever-increasing speeds by ingeniously devised electrical kicks. When the hydrogen ions were finally hurtled out of his cyclotron as from a huge slingshot, they were moving at a velocity which gave them tremendous penetrating power. He at last had a machine that could very well substitute for the tiny radium battering-ram that Rutherford had used in 1919.

With this baby cyclotron Lawrence, in the summer of 1932, made the first serious attempt to invade the nucleus of an atom and produce an artificial transmutation.

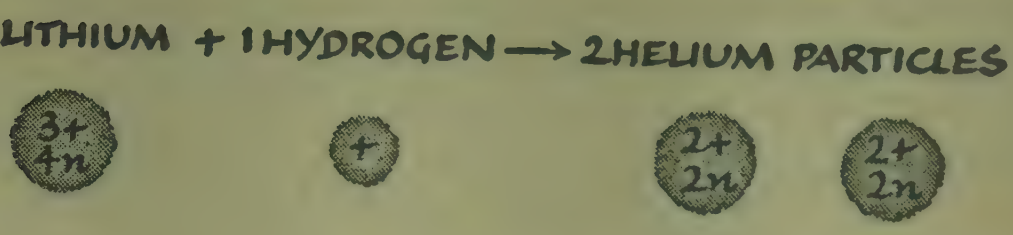
He was tense as he opened the throttle and sent a strea of electrified hydrogen atoms hurtling towards a targ composed of the element lithium. He reached his targ and smashed into the subatomic world. The lithium nu cleus was shattered, and in the debris he detected aton of a different element.



Thus was the first artificial disintegration of an element recorded in the Western Hemisphere. It was not, however, the first transmutation in history performed without the use of another radioactive source such as radium. Lawrence had actually been beaten by a few weeks. The first artificial transmutation in history was accomplished in the Cavendish Laboratory in England, where two of Rutherford's young lieutenants, J. D. Cockcroft and E. T. S. Walton, had used a somewhat different method. They had stepped up their proton bullets to a velocity of 7000 miles a second, not with a cyclotron but by means of high voltages. They, too, had changed lithium to helium. On hearing this historic event Soddy remarked, "The Rubicon of artificial transmutation by means of man-made weapons

which the mind had so lightly vaulted over in imagination from the dawn of civilization was crossed."

This nuclear change can be represented as follows:



Note that this nuclear equation is balanced since there are four protons and four neutrons on each side of the equation.

Lawrence was excited, of course, but eager to try for even more startling effects. He built larger and more powerful cyclotrons. Every available subatomic projectile was hurled against a variety of targets in the hope of breaking into and shattering the nucleus of every element. Protons (hydrogen ions), alpha particles (helium nuclei), deuterons (heavy hydrogen ions), and even neutrons were catapulted into atoms of all sizes and weights with smashing effects. New transmutations were achieved almost daily in his Berkeley laboratory. The dream of the ancient alchemist had really come true. Lawrence could change almost any element at will. In 1936 he changed platinum (element number 78) into gold (element 79) in his cyclotron. Science had turned a new corner. Lawrence was honored with the Nobel Prize in 1939 for these spectacular achievements.

More and more scientists enlisted in this new and exciting field. Newer and more sensational developments were reported so rapidly that atomic research workers were left breathless in their efforts to keep up with all the fresh advances and to study in detail the ground already won. Then on June 4, 1934, exactly one month before Marie Curie died in a sanitarium near Sallanches, the world of science received another jolt from a wireless dispatch to *The New York Times*. It reported a meeting of the Italian Accademia dei Lincei in Rome, where experimental science had stirred once again in the direction hinted at years before.

Speaking at a meeting attended by King Victor Emanuel, Senator Mario Corbino announced the creation of a brand-new element beyond the limits of the the known Periodic Table. It was a transuranium element. It was heavier than uranium. This announcement was met with jubilation in some quarters, but there was also a lifting of scientific eyebrows among many research highbrows. They remembered that at least 33 new elements had been seriously reported by as many scientists in the century and more that had gone by since 1811. In that year, gunonium's discovery was heralded. Seven years later came vestium, then rogerium, nebullium, russium, demonium, asterium, victorium, nipponium, coronium, berzelium, incognitium, cassiopeium, welsium, masurium, illinium, virginium, and alabamine in 1931. Every one of them, however, turned out to be, due to honest errors, premature claims of new elements that actually did not exist. No wonder then that some were skeptical of this newly advertised element.

But the scientist to whose name this discovery was linked was no flash-in-the-pan researcher. He was a young man who had already achieved renown as an atomic scientist. American atomic workers knew him well. He had been over here on two visits during science conventions. Enrico Fermi, born in Rome in 1901, had at the age of 29 become the youngest academician of the Institute of Experimental Physics at the University of Rome. He was a well-known experimenter and theoretical physicist, one not lightly to be dismissed. Scientists all over the world read the report with deep interest. How had he created this new transuranium element?

To synthesize a new complex organic compound was always, of course, a singular achievement, especially if it was as complicated a molecule as, let us say, strychnine or cortisone. But Fermi had apparently done more than this. He had taken on the role of a Creator. He had, it was reported, given mankind a new element that nature herself had not as yet revealed. This came perilously close to being a modern miracle. Nature had provided man with 92 different chemical elements. Out of these building blocks of the physical world every speck of dust

and each galaxy of stars had been created. Could man really manufacture a new element that nature herself had not put together? No wonder men were shaken as never before.

Corbino had reported that young Fermi had used neutrons as projectiles. He had chosen this particle because it was extremely dense, heavy, and electrically neutral—hence it would not be repelled by the electrically charged nucleus of any element. The neutron had been discovered by an Englishman two years before, and Fermi had since then made a thorough study of this newcomer. Neutrons are hard to find. There is no large natural supply. Some of these particles are found in the upper atmosphere as a result of the collision of cosmic rays from outer space with atoms of atmospheric gases. The neutron, moreover, is an unstable particle. Its half-life is about ten minutes. Fermi had, therefore, utilized a stream of neutrons shot out from the metal beryllium when it was struck by helium nuclei, which were emitted during the natural disintegration of a speck of radium.

Fermi and a small group of very young researchers undertook an intensive study of the effect of neutron bombardment on all the chemical elements. They tried the first eight elements and got no results. In the meantime, Fermi discovered the very important fact that he could slow down the speed of neutrons by passing them through either carbon or some compound containing hydrogen. He further found that these slow or thermal neutrons, moving at the speed of only one mile per second instead of 10,000 miles, were more effective in atom bombardment. The ninth element gave some promise of success, and the experiments were continued. Then he came to uranium.

He had hoped that the neutron might penetrate the nucleus of uranium, element No. 92, and leave behind a proton which would be added to the other 92 protons in the uranium nucleus producing an atom with 93 protons or, in other words, a new element, number 93 in the Periodic Table. The Italian Senator reported the experiment had been successful, that a new element similar to manganese had been manufactured and that it fitted in

perfectly with an extension of the Periodic Table in eve respect. Nature had never stored this element here earth, it was believed, since it was very radioactive a had a very short half-life of only 13 minutes. Being unstable it could not exist on this planet for long. Som Italians even suggested that the new element be name *italium* at once.

But Fermi was a very cautious scientist. He made n such claims. The evidence he had before him did not com pletely satisfy him. He thought it might be another variet of uranium. He asked the world of science to suspen judgment, to wait for additional data that might verif his assumptions. He refused to name this "element." H missed something big, so big that the world might hav been different if he had not. The serpent that becam Nazism had already been hatched, and its poison ha spread to Italy. The first antisemitic laws were imported there from Germany. Enrico Fermi, a Roman Catholic had married a Jewish girl, Laura Capon, six years before and having no stomach for Fascism with its suppressio of elementary human rights and its blind acceptance o the nonscientific superior-race theory, determined to leave Italy with his wife and two children.

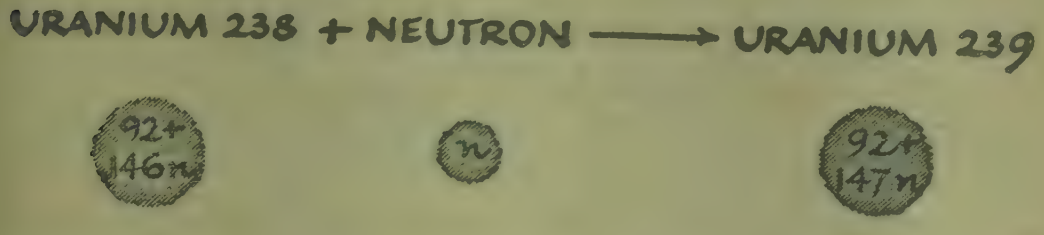
It was not easy. Fortunately, a series of events favored his decision. Just at this moment, he was named a Nobel laureate, and was given permission to travel to Sweden with his family to receive the award. Fermi left Italy and never returned. Instead, after receiving the prize, he took a ship to America, to become professor of physics at Columbia University. Thus Fermi, one of the main architects of the atomic age, became the most distinguished Italian to become a political or religious refugee to the United States.

An old friend of his in Germany, hearing the news, wrote a moving letter to the young scientist. "Thus passes," he commented sadly, "the glory of the Old World to the greater glory of the New World."

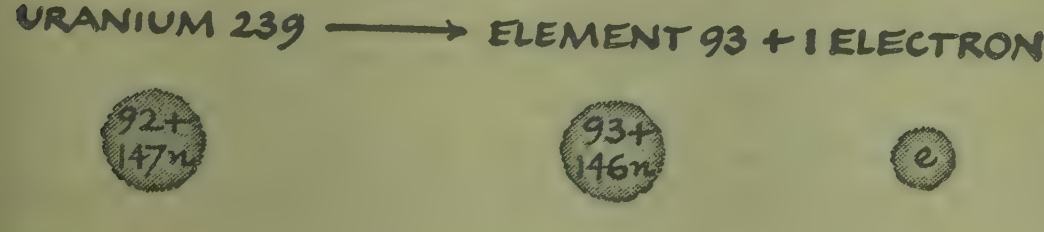
About six years after Fermi's classic experiment, the new element which he refused to claim as discoverer was produced in the United States by an American team. Edwin M. McMillan and Philip A. Abelson, repeating

the experiments of Fermi, shot a stream of neutron bullets at uranium, using Lawrence's cyclotron at the University of California's Radiation Laboratory in Berkeley. Element number 93 was clearly identified as the product. It was exciting enough to have created a new element, but what was even more thrilling was the identification before the end of that same year of still another element, which turned out to be even more interesting. McMillan and Glenn Seaborg learned, while continuing this work, that element 93 actually changed into an even heavier element, number 94.

What happened during the bombardment of uranium with neutrons was that a neutron forced its way into the complex nucleus of the uranium atom, whose relative weight is 238, and formed a heavier type of uranium atom, whose relative weight is 239.

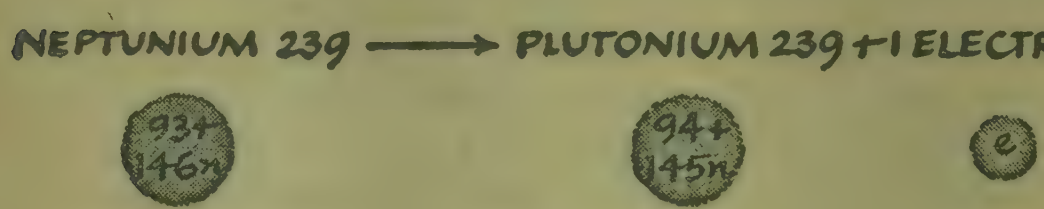


Now this heavy variant of the uranium atom is a very unstable individual. It is composed of a nucleus of neutrons and protons—which happens to be a very bad combination of particles. To relieve the tension in this submicroscopic household, one of the neutrons decides to split up. Every neutron, you may remember, is a close combination of one electron and one proton. This neutron ejects its electron, and the proton part of it stays on. This situation gives the nucleus 93 protons instead of 92. It has become a brand-new element with entirely new properties. In other words, the heavy uranium 239 is radioactive, has a half-life of 23 minutes, and disintegrates spontaneously into element 93, as follows:



As is the practice when a new element is found, t discoverer is given the honor of naming it. McMillan, wh later received the Nobel Prize for this piece of wor christened it *neptunium* (Np) after the planet Neptun which is just outside the planet Uranus—after which th 92nd element had been named.

The atom of neptunium is also a very jittery item, fo half of it, unhappy with its lot, changes spontaneously int another element within less than 2½ days. The new ele ment, 94, is born in the same way as neptunium—tha is, one of its neutrons decides to split into its componen parts, the electron part is ejected from the establishmen while the remaining proton part stays on, and adds to th crowded condition of the proton occupants of the nucleu which is now number 94 instead of 93, thus:



Element 94 was manufactured and identified for the first time late in 1940 by Glenn T. Seaborg and his as sociates working with Lawrence's cyclotron. Following the system used in naming neptunium, element 94 was called *plutonium* (Pu) after the outermost planet of our solar system, Pluto. Two years after its identification "the first pure chemical compound of plutonium, free from carrier material and all foreign matter, was pre pared." When Seaborg got this news he declared that "this memorable day will go down in history to mark the first sight of a synthetic element, and in fact, the first iso lation of a weighable amount of an artificially produced atom of any element." (A few years later both of these elements were detected in natural ores in extremely mi nute amounts.)

Seaborg, who was born in the little town of Ishpeming, Michigan, of Scandinavian ancestry, received his edu cation at the University of California at Los Angeles, and at 28 had already discovered plutonium. This was only

the beginning, for within the next few years he headed several groups of research workers who created seven more transuranium elements. No other man could lay claim to such an impressive record of element building.

In 1944, two new elements were born in the same cyclotron that sat majestically in the Radiation Laboratory of the University of California at Berkeley where Lawrence was chief. Electrified helium bullets whirling around at dizzy speeds were suddenly hurtled against uranium 238 and plutonium 239 and the debris that resulted was examined. Several crack-ups were recorded in each case. Dealing with microscopic amounts of end products, Seaborg and his associates devised highly ingenious techniques of unbelievable sensitivity. They had to, for they were confronted with bits of chemicals weighing much less than one microgram. A microgram is an awfully small hunk of matter—a single dime weighs two and one half *million* micrograms.

When the two newcomers were finally pinned down, identified, and carefully studied for their chemical properties, Seaborg and his co-workers sat down to name them. That was their privilege. One of the three young men working with Seaborg, who remembered all the difficulties and excitement that preceded their discoveries, playfully suggested the names "pandemonium" and "delirium." These were obviously not accepted. For element number 95 Seaborg came up with *americium* (Am), named so because its sister element had been christened europium. Element 96 was dubbed *curium* (Cm) after the Curies because its sister element, gadolinium, had been named after a Finnish chemist, Johan Gadolin.

The public announcement of the discovery of these two elements came in the most unexpected way. The news was to be released in the familiar way before a meeting of the American Chemical Society. But on the preceding Sunday, Seaborg, as guest on the Quiz Kids radio program, was asked by one of the youngsters if any new elements had been discovered. Before he realized what he was doing, Seaborg told five million laymen listening in about elements 95 and 96.

Almost five years passed before two new births were

announced by that same superb nuclear obstetricia Element 97 was born of americium, and christened l Seaborg *berkelium* (Bk) after the city of Berkeley, t home of the cyclotron that Lawrence had given to scienc Then the state in which these deliveries were made w honored with *californium* (Cf), element 98.

After another four crowded years went by came th announcements of still two more new transuranium el ments. Element number 99 (atomic weight 253) wa found to be highly radioactive with a 20-day half-li during which it loses weight and becomes element 9 The great Albert Einstein, father of the new atomic ag had just died, and his illustrious name was given to thi new element, *einsteinium* (Es).

The 100th element of the Periodic Table, together wit the 99th, was first unsuspectedly found in the debris o a hydrogen-bomb explosion set off in 1952 at Eniwetol atoll in the Pacific. Samples of the dust were collected o large filter papers carried by drone airplanes throug the radioactive clouds. The discovery of these elements kept a top secret for more than a year, was achieved b three teams of scientists stationed at Berkeley, Chicag and Los Alamos. Element No. 100 also turned out to be radioactive with a half-life of sixteen hours. Seaborg had, in the meantime, been selected to receive the Nobel Prize for his contributions to creative nuclear chemistry, and some whispered that it might be a good idea to name element number 100 seaborgium. Seaborg protested. Then late in November, 1954, Enrico Fermi, one of the greatest of the pioneers of the atomic age, died of cancer at the age of 53. There was no doubt now in the minds of all the men who had taken part in the adventure of tracking down the new element. It was by common consent named *fermium* (Fm).

One hundred might have made a nice round number of chemical elements to satisfy any chemist. But before the world of science could settle back and glory in the eight new children that had come to romp in their laboratories, another blessed event occurred. The delivery was made in the same 60-inch cyclotron at Berkeley, and the doctor again was Seaborg, aided by four radioactive interns who

caught up by this time, and the end is by no means in sight.

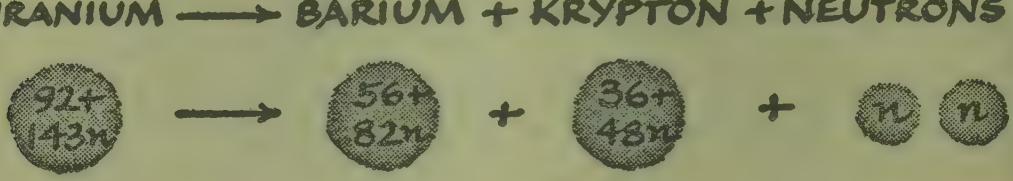
Element 103 is the last of a series of elements called the actinides. These fourteen elements have similar chemical properties. A very sensitive ion-exchange method was developed to separate them in a mixture and to concentrate them for detection and analysis.

You may have been wondering about the uses of any of these newly created elements. With one exception none has been applied in any industrial way. They are all metals, but none of them has challenged the broad and basic uses of iron, copper, aluminum, lead, or any other of our common or even unfamilar elements. As yet they have not even been harnessed to new gadgets, new machines, or new weapons of medicine. They are altogether too unstable. Whatever value they possess lies in the realm of theoretical science. Their creation will help bring us nearer to an understanding of the mystery of matter.

The one exception is the element plutonium. This is the new metal which together with uranium and thorium is changing our lives profoundly. The creation of this new element has added a new dimension to the whole intricate problem of keeping mankind alive. This is the highly toxic and fissionable gift that the chemist has presented to mankind. Plutonium is a metal that in the near future may not only supply the world with a new and powerful prime mover, but it may actually hold the life or death of civilization in its nucleus.

11 A Mighty, New Source of Energy—Nuclear Powe

PLUTONIUM was created by chemists in 1940 and produced on a large scale out of desperation during World War II. Its synthesis was another case of serendipity—the finding of something precious unexpectedly. The story goes back to some experiments carried on at the Kaiser Wilhelm Institute of Chemistry in Berlin-Dahlem only a few miles from Hitler's Chancellery. Here three researchers were repeating Fermi's 1934 experiments with neutrons. Very early in 1939 they were able to report something new in science. Using neutrons as bullets they had bombarded uranium and split its atoms almost in half. The smashup had produced what they had good reason to believe were the elements barium and krypton, and a neutron according to the following nuclear equation:



Barium is a fairly heavy element, well known to chemists and widely distributed as barium compounds. Krypton is one of the colorless, inert gases found in the atmosphere to the extent of about one part in 20 million.

This was an extraordinary piece of news. Hitherto only bits of atoms had been chipped away or added during the transmutation experiments of E. O. Lawrence and his colleagues. But now, apparently, the heaviest of the known elements had literally been blasted into two large hunks. The process was named atomic or nuclear *fission* (Latin *fissio*, a splitting), since the nucleus of the uranium atom had been split almost in half.

What was still more startling even than this spectacular transmutation was the further revelation by these three scientists that their instruments seemed to indicate that tremendous energy was released during this act of fission. The Germans were somewhat at a loss to account for this fact at first and did not bother to pursue it. This was mainly because one of them, the leader of the group, named Otto Hahn, codiscoverer of the element protactinium, was a professional chemist. He was interested only in the deep-seated chemical change that had occurred.

Fermi, too, almost five years earlier was on the very rim of this world-shaking discovery but missed it. One of his young assistants at the University of Rome, Emilio Segrè, many years later, commenting on this episode, said: "God, for his own inscrutable ends, made everyone blind to the phenomenon of fission." As history unfolded, it was indeed a lucky miss. Hahn's latest contribution to science was so revolutionary that in November, 1945, he was named the recipient of the 1944 Nobel Prize in chemistry. Hahn first heard of this honor while listening to the news from the BBC broadcasting station in a British prison, where he had been sent after his capture. It was known in England that he was not in Germany, but his exact whereabouts had been kept a secret. Here in America it was thought that he was among certain German scientists who had been brought over at the close of the war. It was not until December, 1946, that he was finally presented with the Nobel award by the King of Sweden.

One of the trio working in the Berlin laboratory was a mathematical physicist, daughter of a Viennese lawyer. She had been named head of the physics department of the Institute. As the experiments progressed, her mind was concentrated on the energy changes which were taking place. She sensed almost at once that something tremendously important had happened in the subatomic world of the nucleus of uranium. However, she kept her thoughts to herself, for Hitler was on the march. In spite of a lifetime of distinguished scientific work in Europe, during an intensified period of atrocities and purges carried out in the name of racial purity, Lise Meitner, a Jew, was finally

marked by the Nazis for arrest and a concentration cam

Lise Meitner moved fast. Within a few days she "c cided it was high time to get out with my secrets. I to a train for Holland on the pretext that I wanted to spe a week's vacation. At the Dutch border I got by with r Austrian passport, and in Holland I obtained my Swedi visa." She was taking the same road that Fermi was forc to follow. She wanted, of course, to escape the horro of a concentration camp, but even more important, sh wanted desperately to get out of Germany because sh felt she had a secret, an interpretation of the Hah Strassmann experiment that might change the course world history.

Meitner, the physicist, interpreted the data of the e periments in terms of the conversion of some of the stu of uranium into pure energy. This was in accordance wit an idea that Albert Einstein had advanced back in 190 Einstein, in developing his theory of relativity, had de clared that there was really no essential difference be tween mass, such as a pound of lead, and energy, such a light or heat. To him energy possessed mass and matte also represented energy, since a body in swift motio actually possessed more mass than the same body at res He explained that this was of course, a revolutionary an unorthodox idea. Ordinary energy had been regarded a without weight through the centuries because the mass i represented was so infinitesimally small that it was com pletely missed. For example, we now know that the mas equivalent of such a colossal amount of energy as is neede to boil 300,000 tons of water is only a tiny fraction of single ounce. The mass equivalent of the heat energ required to boil a quart of water would, therefore, be almost negligible.

Einstein derived a mathematical equation to expres the equivalency of matter and energy. This now generall familiar equation is $E=MC^2$. E represents energy ex pressed in the unit erg. This unit of work is extremel small. For example, to raise one quart of milk from the floor to a table about three feet high would require abou 100 million ergs of work. M is matter in grams, and C is the speed of light in centimeters per second. This las

named unit is equal to 186,000 miles per second. Now when miles are converted into centimeters and the product is then multiplied by itself, or squared, we get a stupendously large number. Hence *E* or energy becomes an astronomically huge value. For example, one pound of matter—one pound of coal or 16 ounces of uranium—is equivalent to about 11 billion kilowatt hours when completely changed into energy.

This vast amount of energy is roughly equivalent to all the electric energy produced by the entire electrical industry in all of the United States in nearly two weeks. Compare this figure with the *burning* of the same pound of coal (a chemical change rather than a nuclear change) which produces about 4 kilowatt hours of energy, and you begin to realize what a new world was opened up. Expressed in another way, one pound of uranium has the heat value of about three billion pounds of coal when completely converted into energy.

Up to this time scientists doubted whether the energy within the atom would some day be harnessed by science. Ernest Rutherford, who was in a position to know, called the idea "moonshine," and even Einstein, father of the atomic age, was quoted as late as the end of 1934: "I feel absolutely sure, nearly sure, that it will not be possible to convert matter into energy for practical purposes. You must use a lot of energy to get the energy out of the molecule, and the rest is lost. It will be like shooting birds in the dark, in a country where there are few birds." But even an Einstein can be wrong.

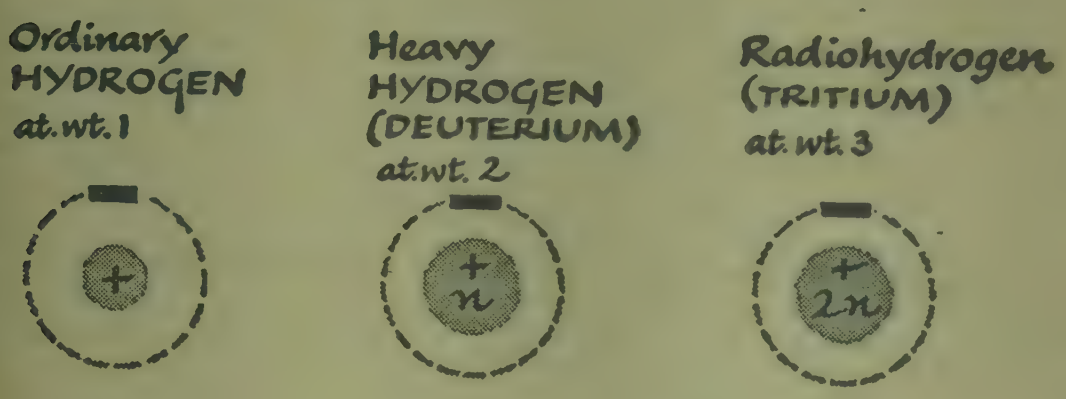
In Stockholm, Lise Meitner communicated her thoughts regarding the energy released during uranium fission to Robert O. Frisch, another German refugee scientist who was then attached to the laboratory of the world-famous atomic scientist, Niels Bohr. Frisch was stirred as he had never been before, and sent the news immediately to Bohr, who had left Copenhagen for the United States where he was to discuss scientific matters with Einstein. Galley proofs of Hahn's key experiment were rushed to Bohr, who also became profoundly affected by this new development and quickly shared his excitement with other scientists, including Fermi.

Within a few days three different American resear groups in different laboratories repeated the Hahn-Stra mann experiment and confirmed the announcement nuclear fission. Bohr discussed it at length with Fer They spoke in German, the one language they could bo speak. Fermi ventured the opinion that nuclear fissi might be the long-sought key to the release of atom energy through the mechanism of a chain reaction. H speculated that during the fission of an atom of uraniu additional neutrons might be liberated, which in tu would attack other atoms of uranium. In this way the might be produced a self-perpetuating reaction. Eac neutron released would disrupt another uranium nucleu just as one firecracker on a string of firecrackers sets o another until the whole mass seems to go up like a to pedoed munition ship in one mighty explosion. Subatomi energy could thus be released, producing, from even 0.1% conversion of one pound of uranium, energy equivalen to that liberated when several million pounds of TN are set off. This huge amount of energy might be har nessed.

Niels Bohr added his own fruitful contribution at thi point. He suggested that only a tiny portion of the ura nium used by Hahn and Strassmann and those who con firmed their experiments actually fissioned because natura uranium used by all of them was really a mixture o several species or variants of the element uranium. These species have the same atomic number or the same num ber of protons, since they occupy only one place in the Periodic Table. Soddy named them isotopes—element in the "same place." They differ, however, in atomic weights because they contain different numbers of neu trons in their nuclei. Isotopes of most of the elements exist in nature. Some elements such as tin are mixtures of as many as ten stable isotopes. Science first became aware of this phenomenon in 1913 when an isotope of lead with an atomic weight of 206 was uncovered by Theodore W. Richards, the first American to receive the Nobel Prize in chemistry. The established atomic weight of natural lead at that time was 207.2.

Even the simplest element, hydrogen, is now known

to occur in three different species or isotopes. Ordinary hydrogen has a single proton for its nucleus. Heavy hydrogen, also known as deuterium, is found to the extent of 1 part in about 6000 in water. In addition to one proton, it has one neutron in its nucleus. The third, named tritium, contains 2 neutrons and one proton in its nucleus, and is known also as radiohydrogen, since it is naturally radioactive. These three isotopes may be represented by the following diagram:



Natural uranium is really a mixture of three isotopes as found in its various ores. Almost 99.3% of it is composed of atoms having an atomic weight of 238. It is, therefore, designated as uranium 238 or U-238. About one part in 140 or 0.7% of the uranium ore consists of U-235, and about 0.006% is U-234. Now, said Bohr, in this natural mixture of uranium only the U-235 is fissionable. In other words, Hahn and his followers had been using a sample of uranium only 0.7% of which could actually undergo fission. The rest of the uranium was actually an impurity which interfered with the total functioning of its U-235. A chain reaction would naturally have a better chance of taking place if pure U-235 were used.

During this discussion Fermi also brought out the fact that the chain reaction would be initated if bombarded with slow neutrons instead of the usual fast neutrons given off when beryllium was attacked with helium nuclei. Fermi, back in the early thirties, had discovered that slow neutrons are a more effective battering-ram. He had made them by placing graphite, a form of carbon, in their path. Neutrons emitted from beryllium travel at the speed of 10,000 miles per second. When, however, such fast-

moving neutrons are forced to pass through some reta
ing agent such as graphite they lose some of their ene
while colliding with the carbon atoms, and they slow do
to a mere one mile a second. This slow neutron n
bounce around from one U-238 atom to another u
it strikes the nucleus of a U-235 atom, whereupon it rea
goes to town. The slow neutron shatters the U-235 in ha
and throws out additional neutrons.

The effectiveness of such a slow neutron has been co
pared to a golf ball that rolls along slowly and drops gen
into the cup on the green, whereas the swiftly moving b
of the inexperienced golfer sweeps over the cup inste
of falling into it. The graphite that is used to slow dow
the neutron is called the moderator. Heavy water contai
ing heavy hydrogen is also an excellent moderator.

No pure U-235 was available at the time anywhere
earth. Isotopes are difficult to separate, since they ha
the same chemical properties and their differences
weight, especially in the case of uranium, are extreme
small. Alfred O. Nier of the University of Minnesota we
to work on this problem and finally separated a tiny spec
(0.02 microgram) of U-235 from its natural mixture. H
sent this to Columbia University where Fermi and othe
used it as a target. The predictions of both Bohr an
Fermi were confirmed in March, 1940. Nier had labore
long and hard to extract this speck of material. At th
rate at which he was able to make the difficult separatio
it would have taken 75,000 years to manufacture a sing
pound of this unusual isotope. But really this pace wa
too slow even for the most patient scientist. The possibilit
of uncorking torrents of nuclear energy remained a dream
It might have remained so for many years had it not bee
that a war was being fought at that moment against th
evils of Nazism.

Disturbing stories were circulating to the effect that Hit
ler had issued orders to his scientists to furnish him wit
several pounds of this fantastic isotope whose tremendou
destructive powers could bring swift world dominatio
for Nazi arms. A few scientists in the United States, espe
cially those who had found refuge here from the religiou
and political persecution of Hitlerism, became terribl

worried. They talked the matter over with Einstein, who was induced to alert President Franklin D. Roosevelt to the power and danger of a uranium chain-reaction bomb. Germany had conquered Czechoslovakia, and its precious uranium ores were in her hands. The most important source of uranium known at that time was in the Belgian Congo. Belgium would undoubtedly be invaded by Hitler's army, and this huge source of uranium would be lost to us.

Roosevelt was reminded that the Germans might very well have already started on the construction of the terrifying weapon. It was known that soon after the discovery of uranium fission the German Ministry of Munitions had got together a research group to examine the possible uses of this new phenomenon in warfare. The team included the top physicists of Germany. Hans Geiger, inventor of the Geiger counter, and Otto Hahn, discoverer of nuclear fission, were members of the group.

Roosevelt saw the clear and present danger and took action at once. A research project was started to investigate the possibility of making a uranium weapon. Then, just before the attack on Pearl Harbor, the slow, leisurely beginnings of this undertaking changed to an "all-out effort to manufacture an atomic bomb." One of the most crucial of the many problems to be solved in this life-and-death venture was the production of a chain reaction that would be self-sustaining and easily controlled. From such a mechanism vital information could be gathered for the men selected to fashion the new bomb.

For this purpose a large, cube-shaped structure 30 × 32 × 21 feet high was designed and set up by Fermi on the floor of the squash rackets court underneath the west stands of Stagg Field at the University of Chicago. It was built of more than half a ton of graphite bricks, each about 4 × 4 × 16 inches.

There was a great deal of theorizing, calculating, discussing and changing of plans. These men were working in a totally new field. There were few guideposts to help them. There was a great deal, too, of piling and repiling of 54 layers of these graphite bricks until the scientists were as black as coal miners coming out of a pit. Thus

came the name *pile* for this device which later develo into the so-called nuclear reactor or atomic furn Fermi's graphite pile contained holes in some of bricks about 8 inches apart, in which were embed lumps of pure uranium metal or uranium oxide. Th in turn were sealed in aluminum cans to protect the tons of uranium from corrosion by the cooling water was pumped through the pile. The structure was rounded by concrete walls to protect the men from d gerous radiations.

A chain reaction will not be self-sustaining unless least one of the two or three neutrons produced dur fission is captured by another uranium atom. Just as c will not continue to burn and its fire will be extinguish when the heat it generates is lost faster than new hea liberated, so a chunk of uranium will not "fission" so lo as it loses too many neutrons compared with the num captured by other uranium atoms for further fission. Ne trons may be lost by being absorbed either by the U-2 in the pile or by impurities found in the uranium or graphite used. U-238 absorbs neutrons but does not fissi hence such neutrons may be considered as lost. Therefo by careful purification of the uranium and graphite use by proper spacing of moderator and target to cut dow further loss of neutrons, and by accurate determination the dimensions of the pile, a self-sustaining chain reacti should, theoretically at least, be controllable.

On the final day of trial Fermi and his assistants sto in front of the control panel of the pile located on a b cony ten feet above the floor of the court. Five contr rods, 17 feet long, extended from openings in the pi Here stood one of the group who was to handle the fir control rod that was to hold the reaction in check shou it show any signs of running amok. Another safety ro automatically controlled, was in the center of the p where a source of free neutrons was to start the furna going. When the panel showed a dangerously high nur ber of neutrons being produced, an electric motor wou be activated to shoot a neutron-absorbing cadmiu plated bronze rod into the pile. As an added precautio an emergency safety rod nicknamed "Zip" was wit

drawn from the center of the pile and tied by a rope to the balcony. An assistant stood by to cut the rope with a single blow if the automatic rods failed to operate for any unpredictable reason. Finally, a liquid control squad stood on a platform above the pile itself, trained and ready to flood the whole pile structure with water containing a neutron-absorbing cadmium compound in solution.

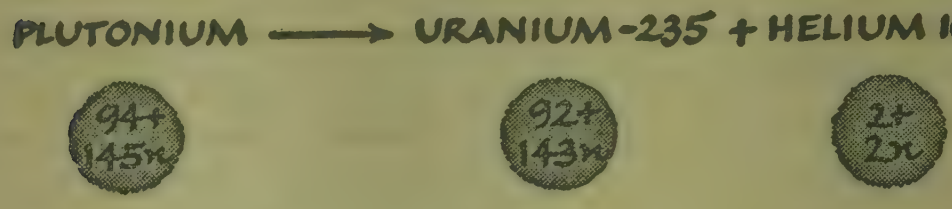
Fermi started the test one morning at 9:45 A.M. by ordering the control rods withdrawn. Six minutes later "Zip" was pulled out by hand. At 10:37 Fermi, still watching the control board, ordered one of the control rods pulled out 13 feet. Half an hour passed. The automatic safety rod was now withdrawn and set. The clicking of the instruments which recorded the production of neutrons and other fission products grew faster and faster. The atmosphere grew more tense. "I'm hungry. Let's go to lunch," said Fermi, and his staff eased off to return to the pile at 2 o'clock that same afternoon. More adjustments, more inspections, more orders and at 2:31 Fermi again computed the rate of rise of neutron count. Then suddenly, quietly yet visibly elated, Fermi whispered, "The reaction is self-sustaining."

For 28 minutes more the pile was kept in operation. At 3:35 p.m. Fermi called out "OK" and the rod was pushed back into the pile to absorb neutrons. It was all over. The assignment that came close to being a new miracle was completed. December 2, 1942, marked the first time in history that man had initiated a successful, self-sustaining nuclear chain reaction. Only a handful of men surrounding Enrico Fermi, who was still technically an enemy alien, knew that on that wintry Wednesday afternoon mankind had turned a corner and changed the course of history.

This first self-sustaining chain reaction was achieved only three months after the first weighable amount of plutonium compound had been prepared laboriously in Lawrence's cyclotron and subjected to careful study of properties. The element turned out to be very stable, with a half-life of 24,300 years, yet sensitive to neutron bombardment and fission. It closely resembled scanty

U-235 in its ability to emit sufficient neutrons to prod a chain reaction.

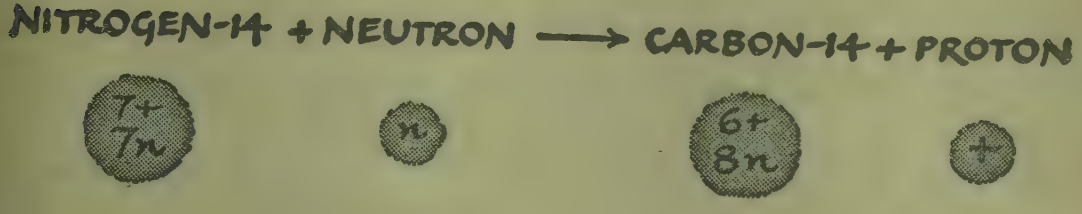
This achievement was of tremendous importance those days of world peril. For here American scient could count on an element which could be separated fr natural uranium much more easily than could that d cult isotope U-235. It could be used together with or a substitute for U-235 in an atom bomb. In fact, the f nuclear reactor was built to produce a controlled ch reaction through which large quantities of plutoni could be manufactured according to the nuclear equat described on page 214. The nuclear equation for the sioning of plutonium with slow neutrons may be writ as:



During the operation of a nuclear reactor a large varie of radioisotopes can be manufactured in large quantiti A radioisotope is any isotope that is radioactive—i.e., d integrates with the liberation of one or more types particles of electron, protons or helium nuclei, or pen trating gamma radiation similar to X rays. The first radi isotope, nitrogen-13, had been created back in 1934 Irène and Frédéric Joliot-Curie, by bombarding the el ment boron with helium. Lawrence's cyclotron had ma ufactured many others, but this factory was very slo and inefficient compared with a nuclear furnace. Fo example, it would take Lawrence's 60-inch cyclotro five full years of continuous operation to manufacture on millicurie (one unit of radioactivity equivalent to tha produced by one milligram of radium) of radioactiv carbon of atomic weight 14. In the pile which the Unite States Government had built at Oak Ridge, Tennessee only 2½ days was required to obtain this yield. In othe instances, the nuclear reactor outproduces the cyclotro one billion times. The cost of radioisotopes accordingl

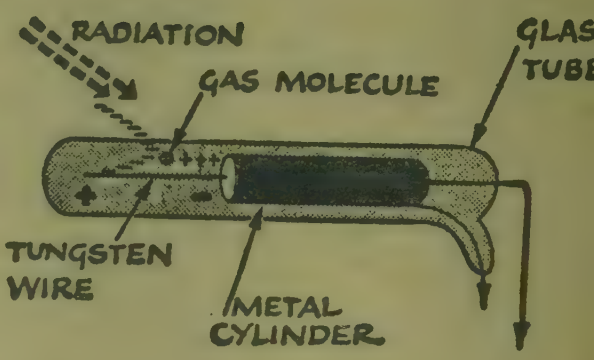
fell at a phenomenal rate with the use of nuclear reactors. Created in the cyclotron, a small speck of carbon-14 (C^{14}) had cost about one million dollars. Manufactured in a nuclear reactor it was worth only a single dollar.

With the invention of the nuclear reactor several hundreds of brand-new atomic species or isotopes were created and identified for the first time. Some of them were made available to research workers. Here chemistry had reached its greatest creative triumph. For the first time in history almost any element could be transformed into radioactive isotopes, in some cases providing several different isotopes of the same element each of which showed different radioactive properties. Most radioactive isotopes are made today by neutron bombardment of the element itself in a nuclear pile. In some instances actual transmutations occur. For example, to make carbon-14, a nitrogen compound such as ammonium nitrate is inserted in the pile. The nitrogen atom in this compound picks up a neutron manufactured in the reactor during uranium fission. The entry of this neutron into the nucleus of the nitrogen atom upsets its balance. The nitrogen atom emits a proton, changing it into a radioactive carbon atom of the same atomic weight as the original nitrogen atom, N-14, thus:



The radioactive isotope is a new, revolutionary, and extremely delicate tool in scientific research. It is used in the so-called tracer or tagged-atom technique. For example, radioactive sulfur-35 can be diluted with ordinary sulfur (atomic weight 32) to the extent of one part in a trillion and still be detected and identified by means of a Geiger counter, which is essentially a detector of nuclear disintegration products. One type of counter consists of an argon-filled tube containing a metal cylinder and a thin wire. Between these two electrodes, a very high voltage is

maintained and so adjusted that the tube is on the ver discharge. When an electron, for example, enters the and collides with a molecule of argon gas, the tube is



charged and a flow of electrons or current is produc This current is amplified and operates a headphone, produces a loud click or flash of light. The greater radiation, or the closer the tube is to the nuclear disin gration, the greater is the effect observed.

Positively charged helium nuclei (alpha particles) a protons, too, are detected by the Geiger counter. Neutr which have no electric charge are detected indirectly w the aid of another tube which contains a compound of element boron. The nucleus of the boron atom abso neutrons and in turn produces other particles which m be detected. Gamma rays such as those emitted by radiu are identified by the same instrument because of the se ondary electrons they produce. A tagged atom can be d tected among millions of ordinary atoms "just as a m with a ringing clock in his pocket can be picked out of silent crowd of 100,000 closely packed people."

Georg von Hevesy, a Hungarian scientist who later b came a Nobel laureate, was the first to employ the trac technique. While involved in experiments on plant meta olism back in 1923 he made use of the elements lead a bismuth which, in their natural state, are slightly radi active. He once used the same technique at a boardi house, where he had reason to suspect the quality of th gate. One morning he brought with him to the dinin

food that was served to him. He decided to investi- room a speck of a radioactive compound and deposited it on a small scrap of meat which he left on his plate. The next day Hevesy returned with the Geiger counter and took his usual place at the dining room table. A dish of hash was brought in by the waitress and placed before him. His Geiger counter started clicking. That was the evidence. It was the same meat that had been left by him on his plate the day before. It is said that Hevesy changed his boarding house very soon after.

Radioisotopes are widely used as tracer elements or chemical sleuths especially in medical and physiological research. For example, radioactive sodium-24 is substituted for the sodium-23 atoms in a bit of common table salt (sodium chloride). This is taken into the body in foods. In about 24 hours the radioactive sodium has completely changed into a new element and has ejected a high-speed particle which can be detected by a Geiger counter placed next to various parts of the body. In this way the itinerary of such a tracer atom can be followed to find the answer to some health problem. Or fluids may be removed from certain parts of the human body and then tested for their radioactivity without disturbing the metabolic process.

Some of the most frequently used radioisotopes are iodine-131, phosphorus-32, cobalt-60, and carbon-14. Iodine-131, whose half-life is eight days, is used not only in studies of cancer of the thyroid gland but also in the treatment of other thyroid disturbances. For example, a person suffering from hyperthyroidism is fed with 0.1 microgram of sodium iodide containing I-131. With the aid of a Geiger counter the rate at which this iodine compound collects in the thyroid gland can be accurately determined. In many cases no surgery is needed.

Radioactive phosphorus (P-32) has been employed in the diagnosis of breast cancer on the basis of an observation that rapidly growing cancer cells seem to take up more of this isotope than do normal cells. It has also been utilized in the treatment of superficial skin cancers, and in the fight against leukemia, a cancerous type of blood disease. In cases of leukemia, P-32 is injected directly into the patient's vein. The treatment is simpler than X-

ray therapy, the infected area can be treated from with the amount of radiation employed can be more carefu and accurately controlled, and the usual nausea and wea ness of radiation sickness that accompanies X-ray thera is avoided. Radioactive phosphorus has also been draft to try to find out how the bacillus of tuberculosis invad the body, how it spreads and produces infection.

Radioactive cobalt of atomic weight 60 became ava able in 1948 for the treatment of deep-seated cance It is very much cheaper than the radium used exclusive up to this time, and has other advantages over the heavi element. For example, radioactive cobalt loses half i radioactivity in about five years and is more than 30 times as powerful as radium. It is taking the place radium and X-ray therapy in the treatment of cancer many hospitals. Lung cancer was also treated with som success by atoms of radioactive gold and zinc.

A few more radioisotopes used in medical and biologic research include calcium-45, strontium-90, sulfur-35, po tassium-42, and iron-59. Iron is helping to clear up th many problems involving shock, and serves also to clarif how hemoglobin of the blood is manufactured and broke down in the human body.

Calcium and strontium compounds are adding to ou knowledge of how bones grow and how milk is produce in man and other animals. The sulfur-32 atoms in sulf drugs have been replaced by sulfur-35 in an effort t learn more about the absorption, movement, and excretio of these drugs in various organs of the body. Potassium 42 is helping to throw light on how various body fluid pass through the walls of living cells, and also how some of the glands, such as the adrenals and pituitary, functio in health and disease. Radioisotopes are finding an increas ing place in the study of the heart diseases.

There are many other peacetime uses of this new nu clear product. Agriculture, for example, is benefiting by the introduction of the fabulous tool. Phosphorus-32 has al ready proved of great value in the many studies being conducted to learn more about how phosphate fertilizers can best be added to the soil to produce larger and health ier crops.

Carbon-14, present in small amounts in nature, has been

a key tool in the unravelling of the mystery of perhaps the most important chemical reaction that takes place in the vegetable world—photosynthesis. This process involves the utilization by the plant of the carbon dioxide of the air and the water in the soil to synthesize starch and sugar in the presence of sunlight, aided by several catalytic agents existing in the plant structure. Extensive researches on photosynthesis with the aid of C-14 were begun in 1946. Ten years later scientists were able to report an almost-but-not-quite complete answer to this very complicated and baffling reaction. A final and complete solution will give science one of the keys for producing food synthetically, an achievement that may ultimately replace the farm by the factory.

Scientific discoveries often follow the most curious turns. Take the case of radioactive carbon-14, which emits electrons and has a half-life of 5360 years. In 1946, Willard F. Libby of the University of Chicago saw in this radioisotope a new method of determining the age of things that date as far back as 30,000 B.C. Wooden coffins and the clothing of Egyptian mummies, charred timber of ancient dwellings, relics, artifacts, bones and bits of charcoal found in prehistoric caves—and, most recently, the Dead Sea scrolls, perhaps 1900 years old—have all been accurately dated by the number of electrons emitted by the carbon-14 they contain.

Carbon-14 is formed in nature by the action of cosmic rays on nitrogen atoms in the atmosphere. This C-14 finds its way into plants as CO_2 and eventually is incorporated into animals which eat the vegetation. The amount of C-14 in plants and animals ceases to increase when the plant or animal dies. A carefully worked out formula relates the emission of electrons from the object under investigation with the time that its C-14 ceased to increase. The method is uncanny in its accuracy. Archaeologists and other students of prehistory regard it as an exciting and reliable new tool of research in time.

Industry, too, has called upon many radioisotopes to solve some of its problems. Synthetic radioactive iron and sulfur are helping steel makers investigate the exchange of sulfur between the iron and the slag produced in the blast furnace in the hope of improving the process. Metal-

lurgists have added several radioisotopes in their resear programs aimed at improving the quality of steel allo The effects of heat and friction on engine wear, rubb tires, and the moving parts of heavy machinery are bei clarified with the help of these new agents. During norm operation iron-59, incorporated in piston rings, is deposit on the cylinder walls. Measurement of this isotope giv a quick and accurate answer to the friction proble Radiophosphorus measures tire wear directly, and sav days of road tests.

Carbon-14 has found widespread use in petroleum r search, where the nature and action of catalysts, the pol merization of hydrocarbons, the flow of undergrou crude oil, natural gas and water, and many other problem are being investigated. Radioisotopes are being introduce too, to control the thickness of sheet metal, coatings o other metals, and paper.

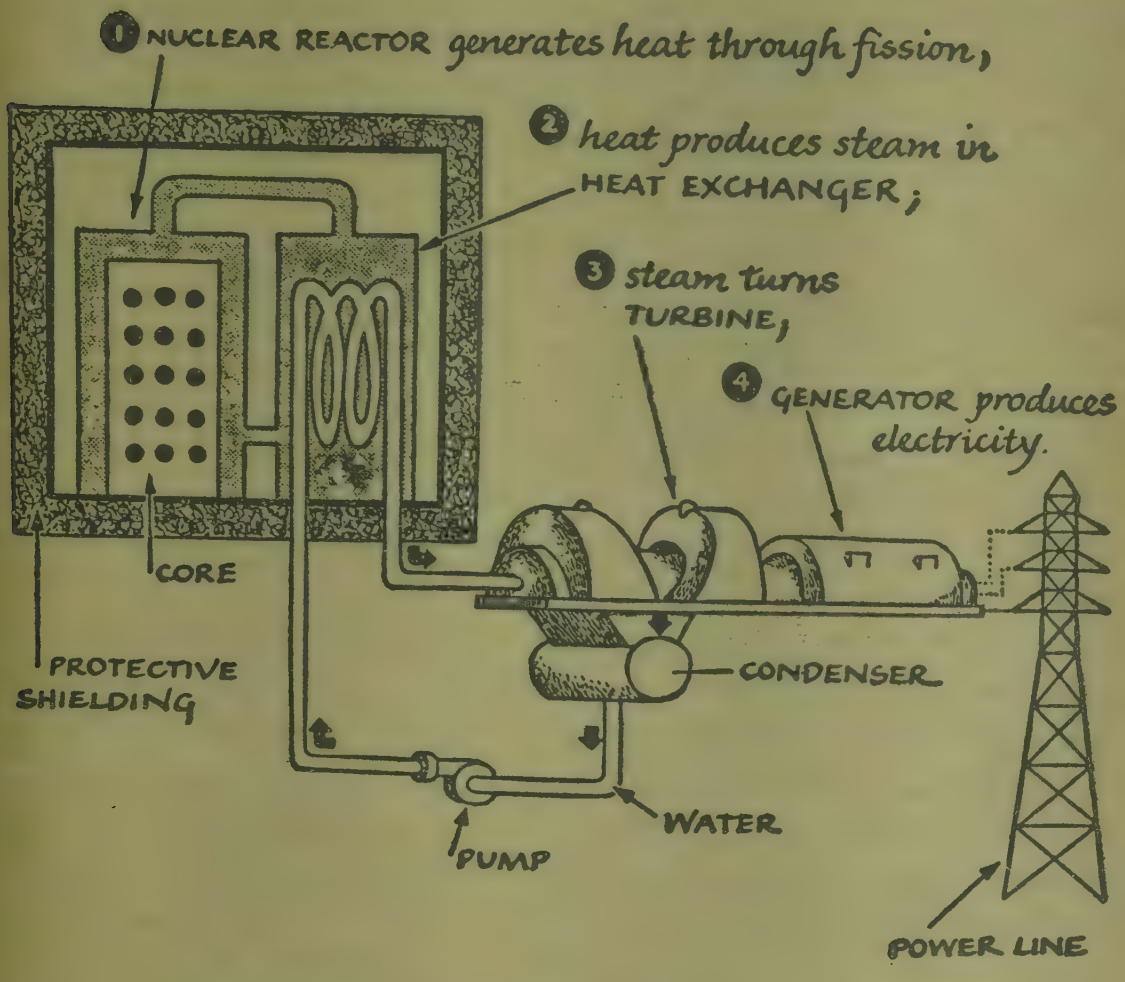
The tracer technique has proved to be of such wide spread and significant value that A. V. Hill, eminent Eng lish physiologist and Nobel prize winner, believes that "th use of such tracer elements will some day be recorded i history as a technique of equal importance with the us of the microscope."

Up to August, 1946, radioisotopes were either unob tainable by most research workers or were prohibitive i cost. At that time, the United States Atomic Energy Com mission began distributing radioisotopes from its Oa Ridge pile to scientists in many parts of the world. Sinc any radioisotope can be flown to any point of the globe i less than two days, practically any radioisotope has be come available to even the most remotely located researc laboratory. Radioisotopes are packed in lead containers the walls of which vary in thickness depending upon th penetrating power of the radiation emitted by them. Thu radioactive iodine, which emits gamma rays—the mos penetrating of all—requires a shield of about 100 pounds while cobalt-60 must be protected in a 1600-pound con- tainer. Several other countries now manufacture radio- isotopes in their own nuclear piles. Among these countrie are Canada, England, France, and the Soviet Union.

This is only a beginning. The future uses of these chem- ical detectives and nuclear healers in the fields of human

health, control of insect pests, plant and insect physiology, the mechanism of heredity, food sterilization, and the manifold areas of industrial research are limitless. A brand-new world of research has been opened up by this creative act of the chemist.

Above and beyond the new and dazzling developments which followed the release of nuclear energy and the construction of the first successful nuclear pile, shines the promise of a new and almost unlimited supply of energy. Atomic power will do the world's work, relieve mankind of the back-breaking operations of mine, mill,



farm, and factory, and raise the standard of living of hundreds of millions of people all over the globe. Every nuclear pile is a potential electric power station. During its operation uranium is fissioning and large quantities of heat are being liberated. This heat changes water to steam which operates a conventional turbine. Electricity is generated and distributed from the nuclear power plant to wherever it is needed.

The three essential parts of any nuclear reactor are the

fuel, the moderator and the protective shielding. The mai fuel is uranium-235, obtained by separating it from th other isotopes of uranium present in natural uranium ore or from plutonium. When U-235 is bombarded with neu trons it fissions and produces heat. The moderator, whic is usually either graphite or heavy water, slows down th neutrons liberated and makes them more effective fo fissioning. The shielding of lead and concrete walls pre vents the very dangerous fission products from leaving th reactor, thus safeguarding the health and lives of its opera tors. Several types of nuclear reactors are already in oper ation, and more are being planned. The nuclear power age has only just begun, and the most efficient type of power plant may be still far off. It may well be that within 10 or 20 years this goal will be reached and the new standard nuclear reactor will be as different from the one in use today as the old Model T Ford is from the sleek and pow erful modern automobile.

Plutonium is a by-product of many nuclear reactors. The first nuclear reactor built by the United States govern ment in 1943 at Oak Ridge, Tennessee, resembled the Chicago atomic pile constructed by Fermi the previous year. A controlled chain reaction was started in this graphite pile with neutrons liberated from a bit of beryl lium metal mixed with radium in the center of the pile. Several nuclear reactions took place, as shown on page 213. When the uranium slugs were ready for processing, they were pushed out at the back of the reactor and new ones were fed in at the front. The slugs fell into tanks of water where the U-239 first produced during fissioning gradually changed into neptunium 239 and finally into plutonium. The slugs were then dissolved in acid and the plutonium chemically separated from the rest of the ele ments present. Since dangerous radiations are produced during these various operations, they are performed by remote control.

A basic method of separating Pu-239 from U-238 had been originally worked out by Seaborg, Emilio Segrè, and two other associates. Because this work had preceded their employment by the United States government on the bomb project, the Patent Compensation Board of the Atomic

Energy Commission in 1955 awarded them $400,000 for their rights to this process.

A second type of reactor was built by the government at the Argonne National Laboratory in Chicago in the form of an aluminum tank six feet in diameter and about nine feet high. The tank was filled with 6½ tons of heavy water in which were suspended 120 uranium metal rods each about one inch in diameter and six feet long. The heavy water, of course, is the moderator in this type. Canada has a heavy-water atom pile in operation at Chalk River in Ontario.

In a third reactor type built at Los Alamos, New Mexico, called a water boiler type, the nuclear "logs" consist of uranium salts dissolved in heavy water, instead of solid rods as in the other two just described. This solution, or "soup," is both fuel and moderator. Heat develops in the water as the chain reaction proceeds. Some reactors such as the one at Oak Ridge are air-cooled, some are water-cooled, like the one built for the government at Hanford, Washington. In some the heat from the uranium fuel core is carried away by water, in others by liquid sodium metal, which is an excellent heat conductor and is noncorrosive to the steel pipe used.

At least 120 reactors are already in use or being built by or for several other countries including Australia, Belgium, Canada, England, France, India, Israel, Norway, Spain, Sweden, Switzerland, and the Soviet Union. Some of these are already producing electricity. This and other startling facts were announced at the United Nations' International Conference on the Peaceful Uses of Atomic Energy first initiated by President Eisenhower, and held in August, 1955, at Geneva, Switzerland.

This meeting with its 1200 delegates and another 800 observers turned out to be more than a conference of top scientists from 74 countries mingling and exchanging knowledge on the peaceful uses of atomic energy. About 400 papers were selected, read, and discussed. The proceedings were published in the four languages of the United Nations. The English version ran to 16 volumes. It was also something of a businessman's gathering, where top level executives and high-pressure salesmen, books in hand, looked for orders for nuclear power plants and all

kinds of instruments for the new nuclear age. Bristish re resentatives, especially, were advertising their readine and ability to design and build nuclear power plants of t various types for any part of the globe. American busines men were somewhat irked at the security system in the own country, which prevented them from reaching into t world markets with products equal to, if not better tha those of their British friends. This unnecessary secre was later eased by the United States Atomic Energy Cor mission, which welcomed private industry as a partner a thrilling adventure.

Marquis Childs, one of the many reporters coverin the Geneva Conference, wrote in his syndicated colum "It is a little as though the use of fire to serve man's wel being had become known ten years ago. And as a resu of this discovery there had been assembled from all th world the first rudimentary cooking pots and other crud beginning devices to turn this new force to practical ad vantage."

The 1946 prediction of Robert Oppenheimer, one o the pioneers in this field, that great nuclear reactors woul be supplying enough energy to heat a large city withi ten years had practically come true. Altogether, ther were some 29 reactors operating in the United States plus three government reactor laboratories in full pro duction in 1955. In January of that year, the first atom powered transport became a reality when the United State submarine *Nautilus* put to sea successfully. This boat and its sister ship, the submarine *Sea Wolf* built soon after may become the forerunners of atom-powered merchan ships, locomotives, airplanes, and such portable nuclear plants as small house boilers and atomic reactors for medical research.

Six months later the first public distribution of nuclear power took place at Arco, Idaho. On the following day, July 18, 1955, the United States Atomic Energy Commission sold the first atom-generated electricity to a private utility. The 10,000 kilowatts of power came from an experimental reactor which had been built at West Milton, New York. The electricity was sent into the public utility lines of the Niagara-Mohawk Power Corporation and was sufficient to supply a city of 25,000 population. As the

giant switch was thrown by Admiral Lewis L. Strauss, chairman of the Atomic Energy Commission, he pointed out that "This switch is a symbol of the great dilemma of our time. I throw it now to the side of the peaceful atom and by that choice we of the United States mark the beginning of a fulfillment of the Scriptural injunction of Isaiah: 'They shall beat their swords into plowshares and their spears into pruning hooks.' "

The year 1955 also saw the dedication of the first privately financed laboratory in the world devoted exclusively to nuclear research. It also witnessed the start of the building of the first full-scale civilian, atom-powered electric plant at Shippingport, Pennsylvania, 25 miles north of Pittsburgh. Westinghouse Electric Corporation built the reactor; the Atomic Energy Commission, sole manufacturer of nuclear fuel and owner of the plant, provided the U-235; and the Duquesne Light Company of Pittsburgh supplied the turbine generator to operate the 60- to 100,000-kilowatt, $50-million plant. Delivery of power to customers in the Pittsburgh area began late in 1957.

The first large-scale privately financed nuclear power plant was built by Consolidated Edison Company of New York. It is also the first thorium power plant in the world. The site of this $100-million station with a capacity of 200,000 kilowatts is Indian Point, New York, on the Hudson River about 40 miles north of New York City. This water-moderated, breeder type nuclear system can supply electricity to about one million New Yorkers.

The Power Reactor Development Company headed by the Detroit Edison Company is building a fast-breeder type nuclear power plant in Monroe, Michigan, with a capacity of 100,000 kilowatts. This station was scheduled to be ready by 1960 and is named after Enrico Fermi. Another group, including the Commonwealth Edison Company, expected to finish its 180,000-kilowatt, General-Electric-built nuclear power station at Lemont, Illinois, in time to supply electricity to the Chicago area at about the same time. Altogether eighteen civilian nuclear power plants have been planned for operation by 1962 with a total capacity of more than a million kilowatts, at a cost of more than one third of a billion dollars of private capital. It is easily apparent that the atom

for power is already in the hands of private enterprise this country.

All this nuclear power is only a beginning, of cour representing less than one per cent of our present install generating capacity. This unusual activity was sparked an offer of the Atomic Energy Commission that year help private industry in the development and operati of nuclear power plants. It offered to lease nuclear fu in the form of U-235 at $11,350 a pound and to provi basic nuclear energy information supplied by its own r search scientists.

The cost of the electricity generated in these nucle power plants will be greater than current costs from co ventional fuels in this country. But as more and more pro ress is made, costs will come down. Said the *Financi World* early in 1956, "Within a decade nuclear powe costs should compare favorably with conventional pla costs over most of the nation." In other parts of the worl this will come even sooner.

As this thrilling new project got under way, experts i the field began to forecast further advances. A technica appraisal task force was set up by our electric power an light companies with the object of maintaining America leadership in this field. It is hoped that by 1970 14% of a new generating plants in this country will be atom powered, and by 1980 this figure should rise to 35%. B the close of the century half the nation's new electrica power, it is predicted, will be generated by atomic fue extracted, refined, and manufactured by American chem ists.

Early this same year Britain, too, was moving ahead i its atoms-for-peace program. In a Christmas message, Si John D. Cockcroft, the scientist who achieved the firs artificial transmutation by man-made projectiles, broad cast his belief that "within two years our nuclear reactor will be delivering very substantial amounts of electricity to industry and our homes. Perhaps by next Christma some of you will even be cooking your Christmas dinne from electricity generated by atomic power." The Britis soon had in operation a 70,000-kilowatt plant at Calde Hall, in Cumberland, supplying electricity to the nationa

power grid. This was her first to be opened when Queen Elizabeth pulled a lever on Oct. 17, 1956.

With three new power plants already under construction —one of them in Scotland—England has committed herself to a 10-year program for building altogether 20 electric power stations to be run by nuclear fuels. Her dwindling coal supplies, which have forced her to import coal from the United States, and her mounting needs of electrical energy which are expected to double in the next 10 years, coupled with her precarious dependence on Mid-East oil dramatically highlighted during the 1956 Suez Canal crisis, made this imperative. Each of the first two constructed by the nationalized Electricity Authority will have an output of 200,000 kilowatts. The total capacity will be more than 5 million kilowatts, and the cost of the program will be about two billion dollars.

By 1965 this program will meet 25% of the growth factor demanded annually by Britain's expanding industry and population. Within the following decade Britain will be building no new generating facility other than nuclear, and will produce 40% of its electricity from nuclear fuel. By 1980 she will be producing atomic energy equivalent to the energy now obtained by coal. In addition, England, already the world's leading exporter of radioisotopes, will also be actively engaged in the exploitation of the new rich export trade in nuclear reactors, fuel and fuel processing equipment, as well as hundreds of radiation and other instruments needed by the new atomic age.

France, too, completed its first industrial nuclear reactor in 1960. This graphite, moderated nuclear furnace has an initial capacity of 60,000 kilowatts, and is located in the Loire Valley of west-central France. By 1975 she is expected to produce about 15-35% of her electricity by nuclear reactors.

Russia turned up at Geneva that same year of 1955 with more than hollow promises. Alongside our full-scale, "swimming pool" nuclear reactor which we had flown to the Conference for exhibition, the young Russian scientists presented a model of her first "commerical" power reactor which, they said, had been in operation for more than a year. Not far from Moscow, it was claimed, the reactor had fed electricity into farms, factories and homes

on a modest experimental scale. The new Soviet Five Y
Plan called for the completion by 1960 of several ato
energy plants with a total capacity of 2.5 million kilow
—equal to that of the United States and England co
bined. These were to be built mainly in the European p
of the Soviet Union, where coal and other fuel are in sh
supply.

The chief of the Russian Atomic Energy Commiss
reported that an atomic ice-breaker was under co
struction, and an atomic whaler would also be bu
Russian leaders also told their people that they are co
pleting the world's largest nuclear power generator, as w
as a new gigantic atom-smasher. This is a $100 mill
synchrocyclotron, located in the Central Institute of N
clear Research at Bolshoya Volga, 80 miles north
Moscow, that has already hurled protons with energies
ten billion volts—about one third that of the worl
largest and heaviest particle accelerator completed
1960 at the Brookhaven National Laboratory at Upto
New York.

What of the underdeveloped countries of the worl
All of the energy-hungry nations are in urgent need
cheap and abundant power. Some of their scientists spo
up. Pakistan and Iraq were interested in small pow
reactors, Brazil and Argentina reported that a shorta
of conventional fuels was holding back their industri
growth. Here was a magnificent opportunity to put th
atom to work for the have-nots and their impoverishe
millions. Three continents were anxiously waiting for hel

President Eisenhower, looking "to find the way b
which the inventiveness of man shall be consecrated
his life," had outlined a little more than a year before a
Atoms-for-Peace Program to the General Assembly
the United Nations. He offered free nuclear fuel on
lend-lease basis with which to build atomic furnaces bo
for experimental and, eventually, industrial uses. Eigh
een months later he doubled this allocation of enriche
uranium fuel to 22 countries including Brazil, India an
Japan. Then early in 1956 he stirred the whole worl
again with the announcement that 88,000 pounds of U
235 would be released for use here and abroad for deve
oping atomic energy for peaceful purposes. Over a perio

of years, half of this huge pile of fissionable uranium would with suitable safeguards be sent overseas to those countries which were not at present making U-235. This, said Eisenhower, was an act of "faith that the atom can be made a powerful instrument for the promotion of world peace."

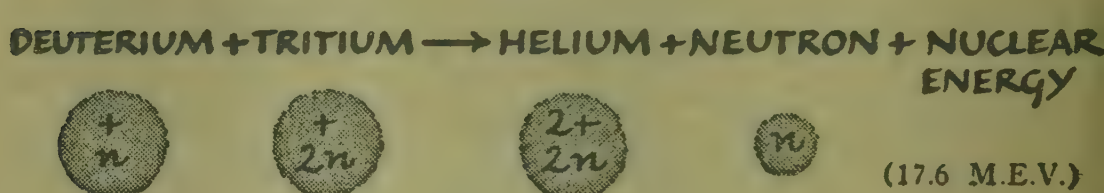
The most spectacular single announcement that came out of the Geneva meeting of atomic scientists was that of Professor Homi J. Bhabha, head of India's atomic energy commission and president of the Conference. Bhabha represented a country where the energy problem is one of the keystones of its future. It is a land where 80% of its energy at that moment came from one of the most primitive methods still in use, the burning of dung, a product which could be better put to use to improve the productivity of her soil. Bhabha was looking even further ahead than the nuclear fission of uranium. "When we learn how to liberate *fusion* energy in a controlled manner," he told his fellow scientists, "the energy problems of the world will truly have been solved forever, for the fuel will be as plentiful as the heavy water in the oceans." Scientists from all over the world were startled. A limitless supply of energy for mankind within two decades was being predicted by a first-rate nuclear physicist. Even men who could see undreamed-of developments in this exploding field of nuclear energy rubbed their eyes and searched for clues and shreds of information on which this almost unbelievable prediction had been made.

To understand this new development we must examine the mechanism of the so-called thermonuclear reaction of the hydrogen bomb, which had already been successfully demonstrated by American scientists in 1952. Soon after the A-bomb, loaded with uranium-235 and plutonium, had been exploded for the first time in history in the summer of 1945, our scientists went to work on another type of bomb, the hydrogen or H-bomb. The principle of this weapon is somewhat different from that of the A-bomb. The destructive force of the H-bomb comes from the *fusion* of lighter atoms into a heavier one rather than from the *fission* of a heavier element into lighter elements.

Two isotopes of hydrogen take part in the fusion process. Heavy hydrogen or deuterium has a mass of two, dou-

ble that of ordinary hydrogen, and radio-hydrogen tritium, the heaviest form, has a mass of three. Heavy h drogen is found in all water, including that of the ocea to the extent of about one part in 6,000. Tritium, with half-life of 12 years, is a synthetic product, and can made in a nuclear reactor by bombardment of the isoto of lithium of atomic weight 6 with neutrons. It is al found in extremely minute quantities in nature, where is created by the bombardment of fast neutrons produc by cosmic rays from outer space on atoms of nitrogen. has been estimated that the total quantity of tritium fou in nature on our entire planet is only two pounds.

The nuclei of deuterium and tritium are made to mer or fuse. During this fusion, the hydrogen is transmut into the heavier element helium, whose mass is four. O neutron is liberated during this fusion, and nuclear ener is produced in tremendous quantities because in fusio too, there is a loss of matter. This thermonuclear reactio may be expressed as follows:



For such a nuclear reaction to take place, however, a enormously high temperature is necessary. Such a tempera ture—about 100 million degrees Centigrade—is foun only in the sun and other stars. In fact, the energy release during the creation of helium out of hydrogen is generall accepted today as the mechanism that produces and main tains the terrific heat of the sun.

This temperature is needed for only about one-millionth of a second to start the fusion process. With the dis covery and control of uranium fission, such a temperatur became available here on earth for the first time. Durin the fission of uranium and plutonium in the A-bomb, cen tral temperatures as high as 150 million degrees Centigrad are produced. The detonation of an A-bomb can thus ac as a trigger for the explosion of an H-bomb, which prob ably contains uranium and plutonium, as well as lithium-6

deuteride. The neutrons (n) released by the A-bomb strike the lithium deuteride (Li-6) and split it into tritium (T) and helium: $Li^6 + n^1 \rightarrow T^3 + He^4$. The tritium and deuterium then fuse as shown in the thermonuclear equation given above. This double bomb explosive can be constructed to provide almost unlimited destructive power since, unlike the A-bomb, the H-bomb is not restricted to the relatively narrow limits of a specific or critical size of an A-bomb. Ordinary A-bombs are in the kiloton or *thousand* tons of TNT class. Hydrogen bombs are in the megaton class, that is, they can produce energy which is the equivalent of as much as 16 *million* tons of TNT.

For the first time in the history of mankind there was presented a real promise of an unlimited supply of cheap energy for the whole world. Here was enough energy to dwarf the total energy of coal, oil, natural gas, running water, and even uranium and thorium. Thorium is an element found in the monazite sands of Brazil, India, the United States and many other parts of the world. It occurs to the over-all extent of about 12 parts per million in the crust of the earth. Thus it is at least four times as plentiful as uranium. Thorium is not a fissionable element, but it is a "fertile" metal—that is, it can be rendered as fissionable as uranium-235 or plutonium by being transmuted to uranium-233, which fissions when struck by slow neutrons in a nuclear reactor. A thorium reactor can actually breed more fuel than it burns.

It became known at Geneva that an atomic race of a different sort was on. The United States, England, France, and the Soviet Union had already embarked on extensive research work to try to harness the energy of a thermonuclear reaction for peaceful purposes. There was some uneasiness apparent among those present at the Geneva conference who were thinking in terms of huge investments in the nuclear energy industry that was being born. Would the brand-new uranium, plutonium or thorium reactors being designed for the brave new world that was just around the corner be obsolete even before they had been completed? Billions of dollars of investors' money were at stake. Were their "conventional" atomic reactors to become, in no time, the Model T's of the deuterium-tritium age that was coming up so fast? Was it safe to in-

vest in uranium power plants?

Prospectors, processors, investment brokers, and in tors by the thousands in uranium ore stocks began to h nightmares. We were digging three million tons of urani ore out of the ground each year. The United States stockpiling uranium like mad. We were in the thr of a virulent uranium fever. Thousands of people—min sheep herders, clerks, gasoline pump attendants and sa men were swarming over the 100,000 square miles of Colorado Plateau. They were searching for uranium w Geiger counters, drilling test holes in every acre of desert rock in canyons and mesas, and recording clai galore. What if there was a sudden break-through in t new fusion research even sooner than Bhabha had p dicted? Billions of dollars of investments might go do the drain overnight if tritium replaced uranium. Sob scientists in the know quieted them. They were remind of the scores of stupendous difficulties that lay ahead this long-range project. Perhaps, said some, it would nev be solved, for it was an infinitely tougher job than even t fission control undertaking had been. Uranium and th rium were still to be relied on as the fuel of the near futu

All agreed, however, that the conquest of nuclear *fissi* would usher in a new and far greater industrial and soci revolution, especially in the backward countries of t world. This conquest was, of course, a scientific triump of no mean proportion. But there were some bold spir who saw nuclear *fusion*, too, within our grasp. Said S John Cockcroft in a lecture at the Geneva meeting: "M faith in the creative ability of the scientist is so great th I am sure that this (power from fusion) will be achieve long before it is essential for man's needs."

In the meantime, there is a ferment in laboratories a over the world. Scientists are still picking the nucleus the atom apart and trying to put together the 30 or mo subatomic particles already discovered or predicted, to se how the atom really ticks. Creative chemistry is in th middle of this great adventure, too, and will continue t be equally fruitful in many other areas where chemists ar looking for products which nature, in all her lavishnes just forgot to create.

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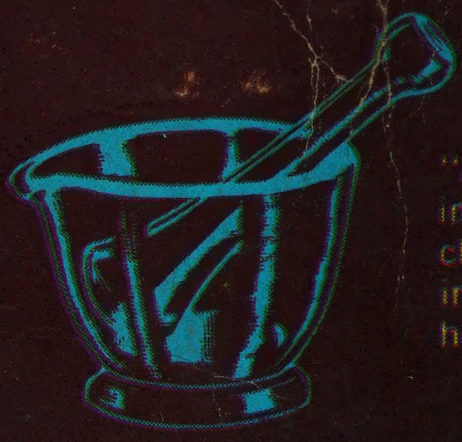

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